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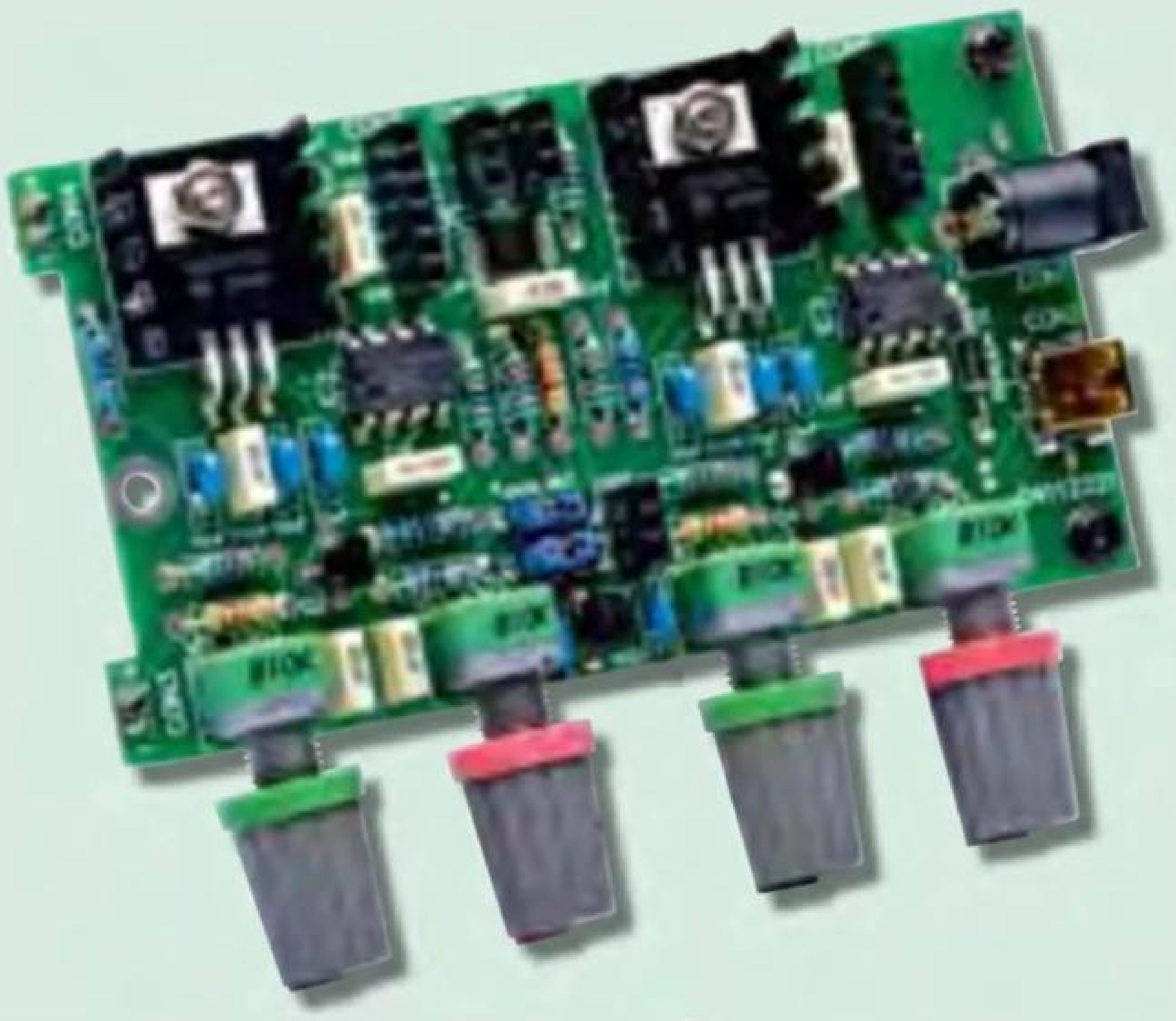

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This board lets you use a PIC18F18146 8-bit microcontroller for any task while its onboard peripherals generate an adjustable voltage without interfering with what it's doing. It includes capacitive sense buttons and a seven-segment display.

Dual-Channel Power Supply for Breadboards by Tim Blythman 25
This Dual-Channel Breadboard PSU plugs straight into a breadboard's power rails, has two adjustable current-limited outputs and can run from different power sources.

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The January 2024 issue of *Practical Electronics* will be published on Thursday, 7 December 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by **LOUIS MEULSTEE**

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

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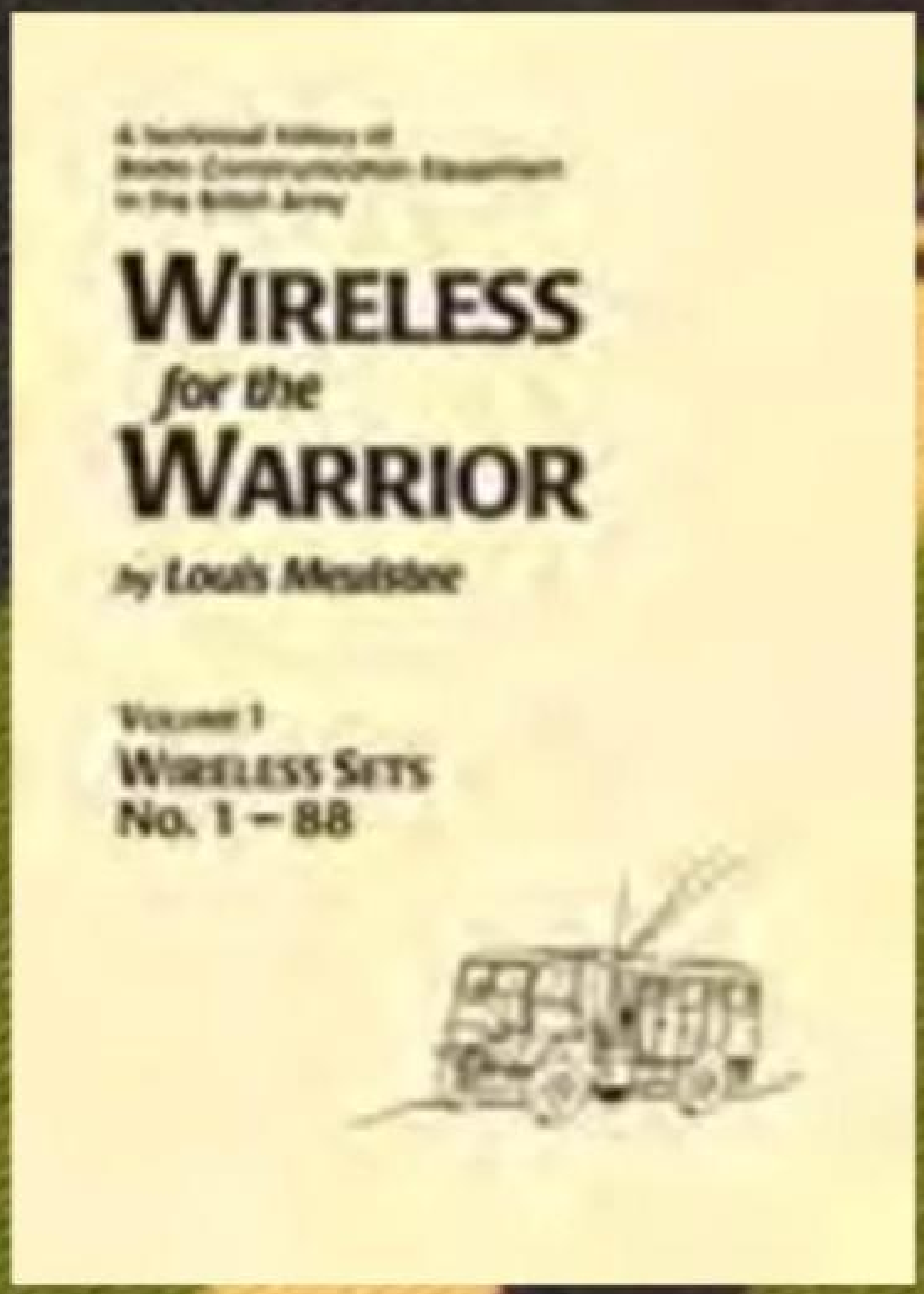
Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.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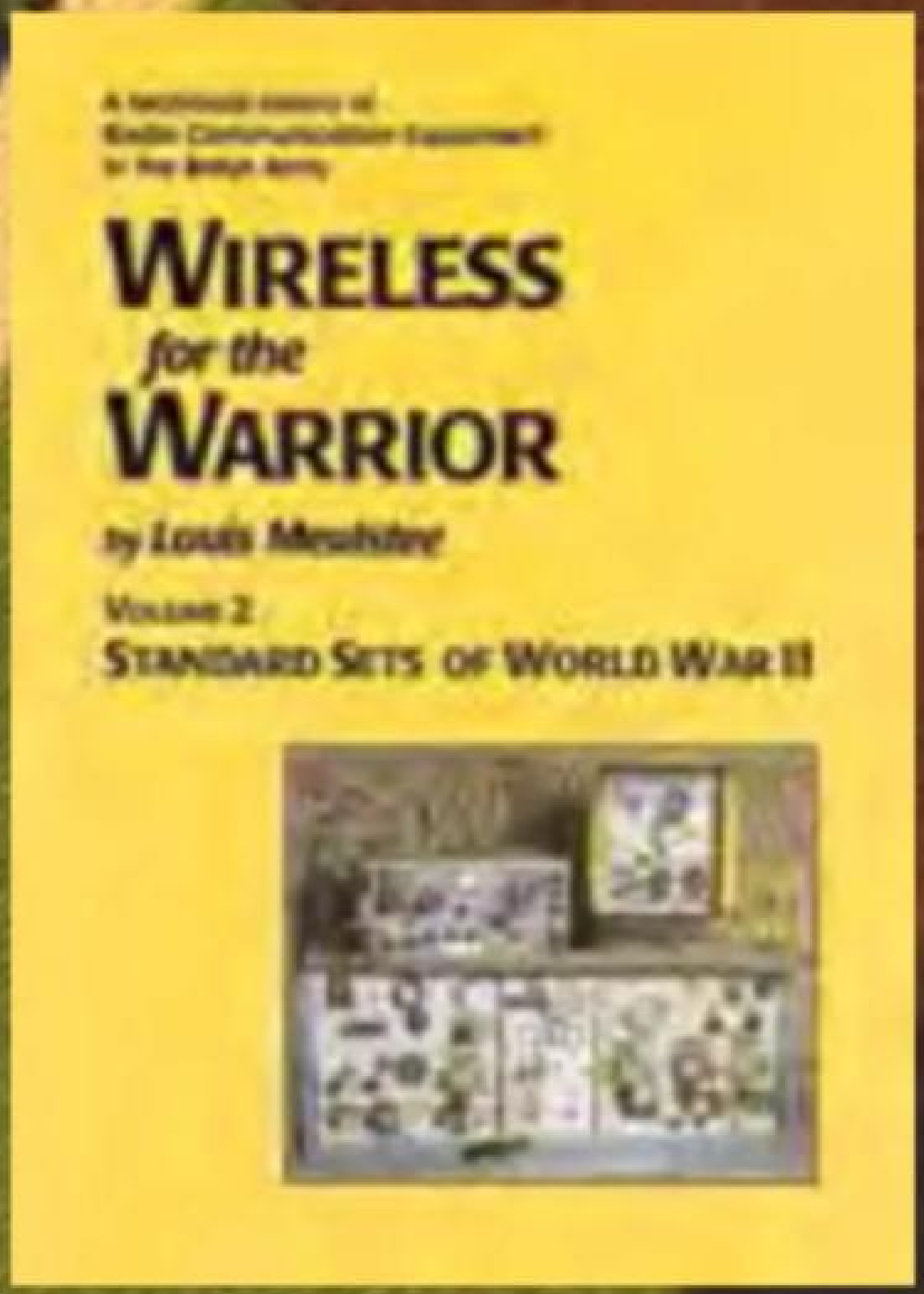
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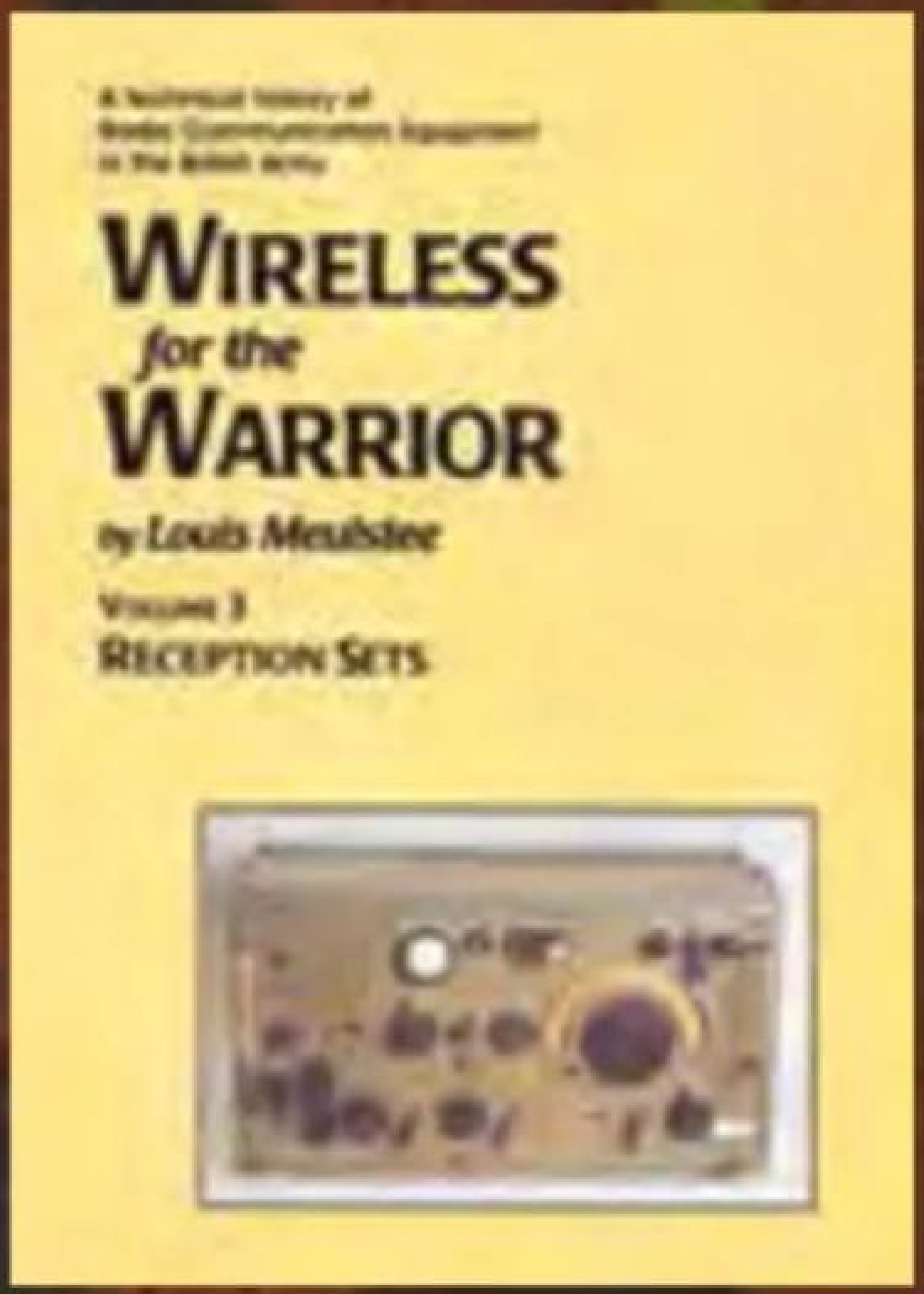
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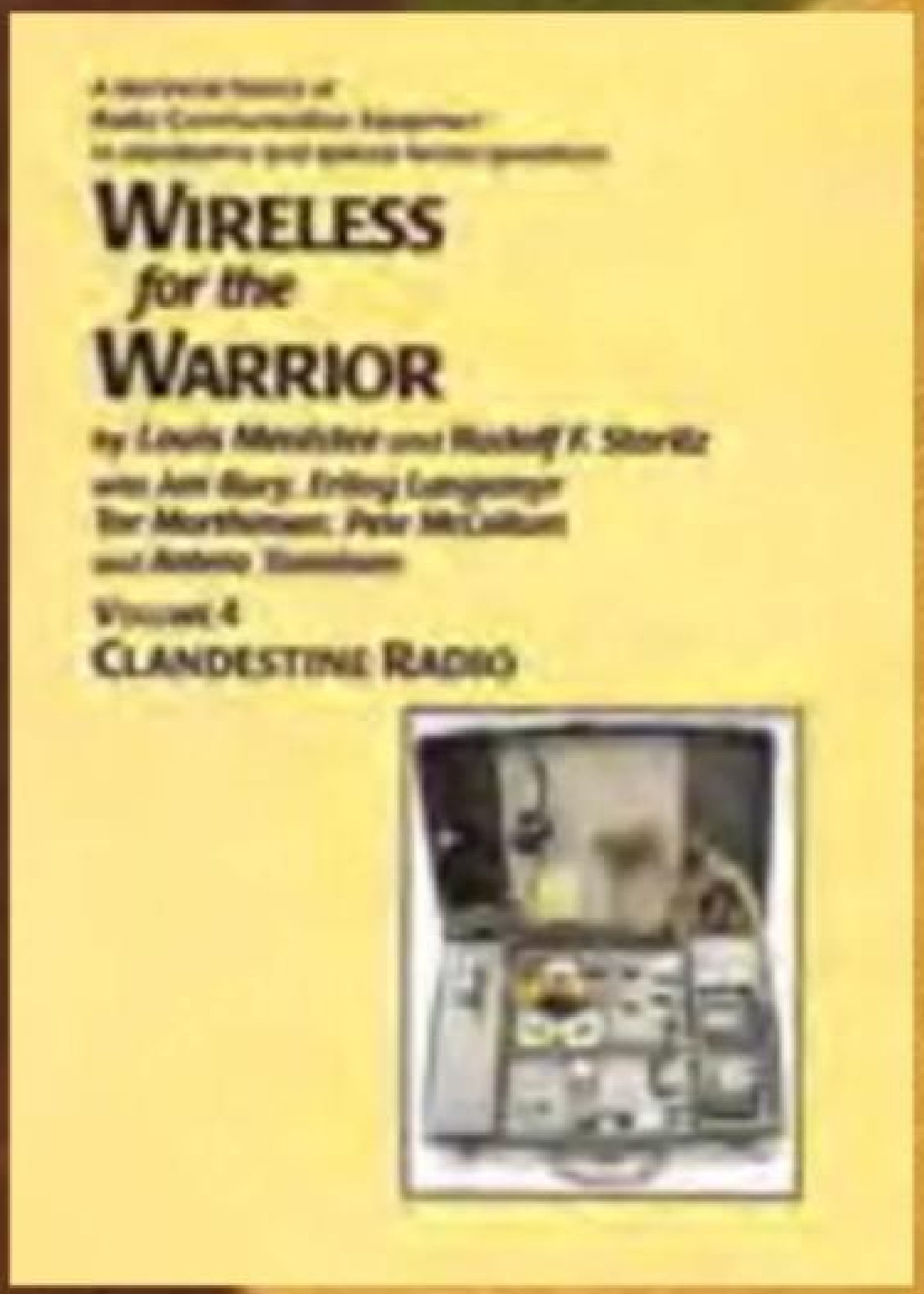
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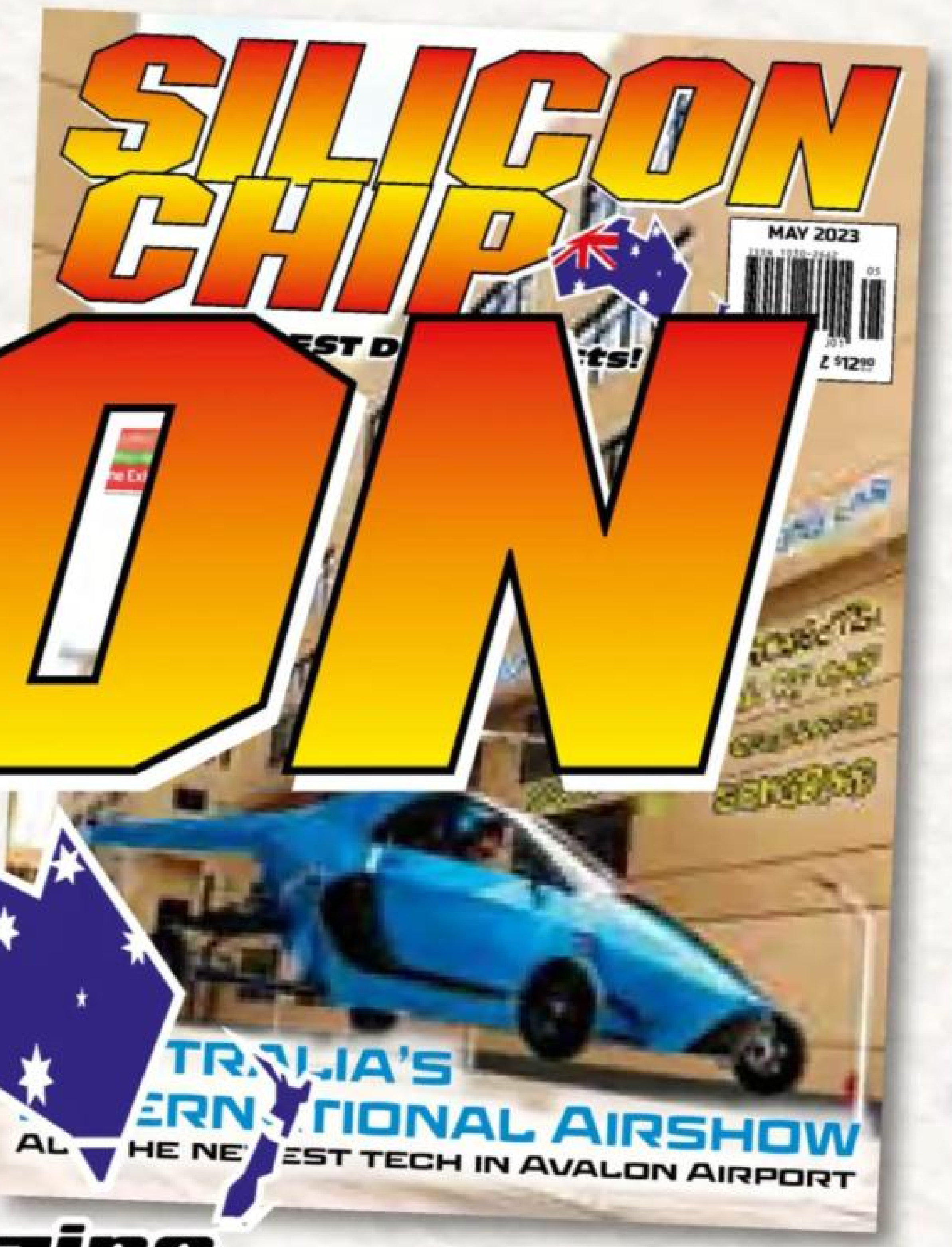

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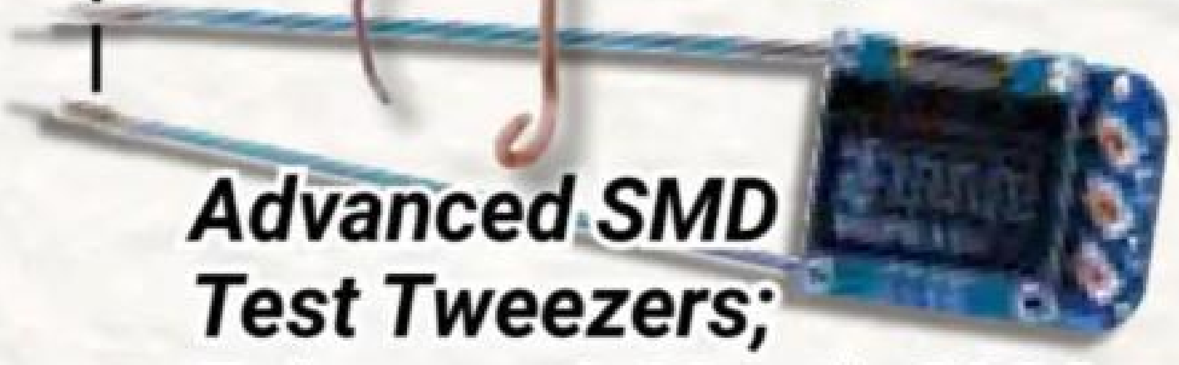

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Amazing electronics

It’s so easy to take electronics for granted, even though it is one of the most extraordinary technological and scientific marvels ever created. In just a few decades we have progressed from thermionic tubes to integrated circuits boasting features measured in nanometres. We know it’s amazing and yet we so quickly get used to the pace of change that it takes a lot to impress us. I recently had reason to consider this when I bought an Apple Watch, principally for health reasons.

First, a little background: my doctor had told me that I needed to lose weight and do more exercise. I enjoy cooking as much as I dislike exercise, so the thought of eating less and exercising more was not welcome, but the doctor was serious and warned me that sooner or later I’d need to do this, or it would affect my health. He suggested a regime based on calorie-controlled, but nutritious, shakes and a choice of exercises. A friend suggested I get some kind of sports watch to track my exercise.

So, armed with some pretty unappetizing shakes, a watch and not much of a clue about exercising I decided to turn this into a personal project to find out just how good a job modern electronics makes of monitoring the human body.

To be honest, I wasn’t that optimistic. A background in instrumentation engineering had taught me that measuring even well-defined straightforward parameters such as speed, temperature and pressure takes a lot of skill and effort if you want to get good, reliable results. Measuring the kilocalorie (kcal) burn of the human body sounded horribly complicated and error prone, but perhaps it would be fun to find out if the current state of the art of ‘wearables’ justified all the claims made for them.

My plan was simple. The shakes were designed to provide a specific number of kcals per day, my watch’s blood flow / oxygen sensors, accelerometers and gyroscopes, coupled with some (hopefully) sophisticated motion and blood analysis software would tell me how many kcals I had burned. The resulting mathematics was simple: 7,700 kcals represents 1kg of body mass lost (or gained) depending on whether you eat more or fewer kcals than you exercise.

Well, the results are in, and I am beyond amazed. My watch is incredibly accurate. Over six weeks I measured and logged my data very carefully. Everything I ate was converted into kcals and subtracted from what my watch had told me I done in terms of exercise. I compared the results with my electronic bathroom scales (a good set made by a reputable company), and the watch was better than 90% accurate. I find that extraordinary. A tiny piece of electronics resting on my wrist can analyse my movement and blood (non-invasively) and from that generate extremely accurate data of what I am doing.

Matt Pulzer
Publisher

Good grief! Is that the time?

Techno Talk

Max the Magnificent

It's often not sufficient to simply know that something has happened – the key is knowing when it happened. When there are hundreds or thousands of events, establishing and measuring their level of simultaneity or temporal ordering can be… tricky.

In an earlier Techno Talk column (*PE*, October 2023) I introduced the concept of Precision Time Protocol (PTP), a.k.a. IEEE 1588, which can be used to synchronise all the nodes in a packet-based network with an accuracy in the sub-microsecond range.

Just thinking about how this works boggles my mind. We start off with a 'grandmaster clock,' which will probably derive its notion of time from some global navigation satellite system (GNSS) source. All the downstream nodes in the network will maintain their own local time-of-day (ToD) clocks, often with battery backup, but how do we (and they) know how accurate they are?

This is where PTP enters the picture. The network node associated with the grandmaster clock will send a data packet to one of its downstream nodes. This packet will be timestamped as it leaves the grandmaster and timestamped again on arrival at its destination. The downstream node will then return the packet to the upstream node (the grandmaster in this example). Once again, the packet will be timestamped both on departure and arrival. By means of these four timestamps, the upstream node can (a) calculate the round-trip-time of the packet and (b) determine any error in the downstream node's clock. The upstream node can subsequently transmit a control packet to the downstream node saying something like 'You are xxx out of sync, so set your local time-of-day clock to yyy.'

Of course, things are a lot more complicated than I've made them sound here. For example, different packets can take different routes through the network. Also, each upstream node may have multiple subservient downstream nodes, and each downstream node may be seen as an upstream node to other nodes that are further downstream, if you see what I mean.

Feelin' the strain?

The reason I've been waffling on about PTP is that I just discovered its use is not limited to things like 5G radio access networks (RANs). I was talking to the chaps and chapesses at VTI Instruments. These little scamps design and deliver data acquisition and functional test solutions for anyone designing large structures like wind turbines, airplanes and small modular reactors (SMRs), which are small nuclear power stations with power generation capabilities in the 30MW to 300MW range.

Strain gauges were invented by Edward Simmons and Arthur Ruge in 1938. The most common type of strain gauge consists of an insulating flexible backing that supports a metallic foil pattern. The gauge is attached to an object of interest by a suitable adhesive. As the object is deformed, the foil is deformed, thereby causing its electrical resistance to change. By measuring this change, it's possible to determine what's happening to the structure to which the gauge is attached.

The folks at VTI make a 16-channel precision bridge and strain gauge unit. To minimise errors, these units need to be placed close to the strain gauges they are monitoring. 'Not a big problem,' you may think. OK, but now suppose I tell you that the folks testing a large prototype aircraft may have up to 10,000 strain gauges in play at any one time. This means they need 625 of these 16-channel strain gauge units.

LAN eXtensions for Instrumentation (LXI) is a standard developed by the LXI Consortium, which maintains the LXI specification and promotes the LXI Standard. This standard defines the communication protocols for instrumentation and data acquisition systems using Ethernet.

VTI's strain gauge units employ the LXI standard to transport the data they are reading over Ethernet cables. Obviously, we don't have 625 of these cables feeding directly into a server. Instead, groups of (say) 16 cables will be fed into a bunch of 16-port Ethernet switches. There will be a hierarchy of these switches leading to the main server. Also, as opposed to deploying 625 power cables, the 16-channel strain gauge units employ Power over Ethernet (PoE).

But the really important point about all this is *timing*. Suppose the team is performing a structural test to determine when a wing will break, for example. In this case, it's not sufficient to simply know the readings on all the strain gauges over time – it's critical to know the exact times associated with each of the readings. You can only imagine my surprise to discover that VTI's strain gauge units include support for PTP/1588, thereby allowing the times of, and relationships between, events to be determined with sub-microsecond accuracy.

Can't take the pressure?

Suppose we are building a small nuclear reactor like one of the aforementioned SMRs. One thing we can expect to find at the heart of the SMR will be a lot of pipes. For example, there will be a coolant circulation system that powers the turbine that drives the generator that produces the electricity. Some SMRs use water as a coolant. Heated by the reactor core, the water turns into superheated steam that powers the turbine. Other SMRs may use gas, liquid metal, or molten salt as coolants.

Not surprisingly, we are going to be interested in the pressures at various points in our piping networks. Also not surprisingly, we are going to be reluctant to use standard pressure gauges, which will oblige us to drill holes in our pipes. Every hole and every weld are potential points of failure. The solution, once again, is to employ strain gauges. Measurements from strain gauges can be used to determine stress, deflection, torque and deformation. In the case of pipes, deformation can be used to ascertain the pressure of the fluid (liquid or gas) in those pipes.

My eyes have been opened

I was introduced to strain gauges when I was a student in the dim and distant past. I must admit I didn't hold them in particularly high regard at that time, but I think it's fair to say that my eyes have been opened to a world of possibilities.

Win a Microchip PIC24F LCD and USB Curiosity Development Board

Practical Electronics is offering its readers the chance to win a Microchip PIC24F LCD and USB Curiosity Development Board (DM240018) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The PIC24F USB and LCD Curiosity Development Board is a cost-effective, fully integrated development platform that helps you explore segmented LCD interfacing and various features of the low-power PIC24F MCUs with a USB and integrated LCD controller. Designed from the ground-up to take full advantage of Microchip's MPLAB X IDE and MPLAB Code Configurator (MCC), the board includes an integrated programmer/debugger and requires no additional hardware, simplifying your prototyping.

Worth $69.50 (approx £56.00) each

The PIC24F USB and LCD Curiosity Board is the perfect platform to harness the power of the PIC24FJ512GU410 low-power microcontroller with a USB and LCD controller. Its layout and external connections offer unparalleled access to the Core Independent Peripherals (CIPs). The on-chip CIPs enable you to integrate various system functions onto a single MCU, simplifying the design and keeping system power consumption and BOM cost low.

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Closing date

The closing date for this offer is 30 November 2023

August 2022 winner

Harry Sparrow

He won a Microchip SAM9X60 Curiosity Development Board

Net Work

Alan Winstanley

Our *Net Work* columnist tries some compact uninterruptible power supplies designed for routers, modems or small electronics during a power outage. How the UK would manage power shortages using a system of 'regional blocks' is also described, and there's more space news.

This month, we start with the price of power: 'The cost of electrical energy consumption has become increasingly significant in recent years as the price of primary fuels has risen more quickly than the average increase in the cost of living. In order to control costs in the house, it is necessary to know which appliances cost the most to use and to what extent savings can be made by reduced usage, turning thermostats down, etc.' Those words could have been written yesterday, but were actually the opening lines of a constructional project, the *Telectric Electricity Cost Monitor*, featured over 40 years ago in *Practical Electronics*, March 1982. Mindful of the need for consumers to monitor energy bills, this complex project used an 8035 microprocessor and a 7-segment LED readout programmed to display the running costs of a single appliance, at a time when electricity costs were about 15% of what they are today, although the demand for gas still outstripped the available supply, even back then.

The question of electricity running costs is still very relevant, and modern plug-in successors to the *PE Telectric* are commonly available online for £10 or so. They display power used, voltage, current, power factor and running costs. While modern electronics may consume negligible power (under a watt) when on standby, many devices such as routers or telephone handsets are left running 24 hours a day. This started me thinking about my four wireless mesh hubs that are dotted around the house. Each ITE (Information Technology Equipment) mains adaptor is rated at 9V, 7.6W; if something operating 24x7 consumed just 6W then it would use one unit or kWh per week, costing about £14 a year each, or £56 annually for all four. Add a crop of smart speakers and a smart display or two (some rated up to 30W – costing up to £65 a year, say), a modem, a pretty warm Devolo PLC adaptor or two, a switch or network hub, and the running costs of home networking devices soon mounts up significantly.

Of course, we can only know a device's actual power usage by logging its current consumption, but a typical 'smart' household probably spends hundreds of pounds a year powering these devices alone. For now, I've unplugged a wireless mesh hub or two, dumped an old clock radio and other unneeded mains electricals which will save a further £50 a year, and I make sure nothing is left on standby unless it's absolutely necessary.

A compact UPS solution

In October's *Net Work* I described how my router suddenly stopped working late one evening, taking my entire network down with it. The fault was traced to a failed switched-mode mains adaptor, so I found a neat 'Zolt' 34W multi-voltage adaptor that came with a range of DC connectors. Unlike some dubious-looking imports, this model is UKCA type-approved, seems to be well made and it has done the job admirably so far. I then realised how my entire home network relies on just two mains adaptors, one for the router and one for a separate modem, and if either of them failed then nearly 20 network or smart devices would be rendered useless.

The iPower-H from Power Inspired Ltd is a 12V uninterruptible power supply offering up to one hour of UPS protection through its built-in battery. Available in UK or Euro mains adaptor styles.

By sheer co-incidence, I'd recently had an annoying two-second mains outage that knocked out the network for five minutes

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An adaptor lets 2.1mm (ID) DC plugs fit into a 2.5mm DC jack.

or more while the router and network reset itself, and some smart devices took longer to re-establish themselves properly again.

For desktop computer users, an uninterruptible power supply (UPS) will safeguard against data loss or crashes if mains power is interrupted or there's a brownout, and it will also protect against surges when power is restored again. It buys you time to save work in progress and the computer can then be shut down gracefully. Brands include APC, Salicru, Eaton and Cyberpower and they generally have IEC mains outlets for operating a monitor and PC for a period of time. My Salicru SPS SOHO+ 1200W will power my PC and monitor for some tens of minutes and its USB port allows PC software to monitor the battery status and log data. I also use red-coloured IEC mains leads to indicate which supplies are UPS-protected, and I might turn the UPS off at the mains once or twice a year to exercise the battery. How long the internal battery will last before it's scrapped is down to pot luck (five years, say), and replacing them can be non-trivial or even impossible.

With smaller peripherals such as storage drives, IP cameras and routers in mind, a range of compact UPS products has evolved that are designed to power individual devices during power interruptions. I recently received two samples kindly offered by Power Inspired Ltd, a UK manufacturer based near Oxford, who make a range of very interesting power supplies and accessories. I've been testing them over the past few weeks, starting with their iPower-H, which is a plug-in 12V mains adaptor with a difference: it also contains a 3350mAh Li-Ion battery which can provide an uninterruptible 12V DC supply at one amp (or 25W peak) for up to an hour or so. This battery back-up adaptor can protect ITE equipment like a low-power router or ONT (Optical Network Terminal) modem, or security devices, CCTV and so on – anything needing 12V DC at up to 1A or 2.1A peak. It's slim enough to fit onto a crowded multi-way power strip, and it has a multi-state LED to display status. Pressing a small pushbutton for a few seconds will toggle the DC power on and off.

Fit for purpose

This UPS adaptor can be used with 90-264V AC mains at 50/60Hz and comes pre-fitted with either a UK or 2-pin Euro mains plug. It has a lengthy (2m) DC lead terminated in a 5.5 x 2.5/2.1mm DC plug of the sprung, bifurcated variety that I described back in the October issue. It will therefore fit most 12V equipment and it powered up my router without any issue, charging up within an hour or so.

Users might also want to power a separate modem as well, if it's not already built into their router. As my modem also used a 12V supply, eventually I found a DC Y-splitter cable which is commonly used in CCTV set-ups. This would allow the iPower-H to operate both the router and modem for a reasonable period of time. These DC splitter cables (up to 9-way!) are readily available on the usual Internet sites, including my suggested supplier, Kenable Ltd, who offer a very keenly-priced range of DC and CCTV leads. Kenable will also be found on eBay, but here is their main site: **www.kenable.co.uk**

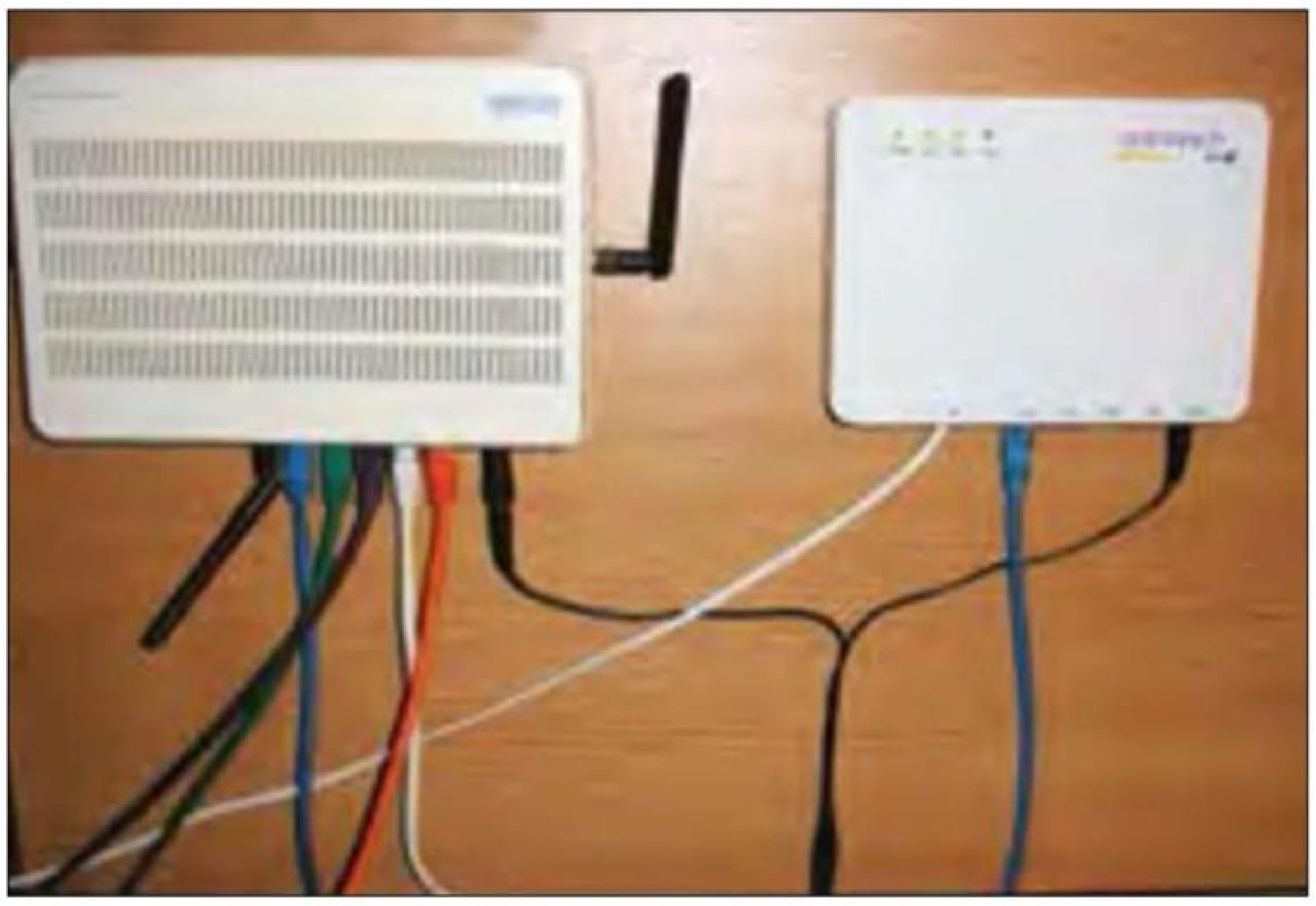
To hook the modem and router to the UPS, I grappled with various DC plugs and splitter cables, learning a few things along the way. In my case, the main stumbling block was that my router has a 5.5 x 2.5mm DC jack, which I found out through trial and error. However, the CCTV sector seems to use 5.5 x 2.1mm DC plugs, so the splitter cable would obviously not fit into my router DC jack as the plug's ID was too small. Again, the CCTV market had an answer, as an adaptor plug is sold that reduces a 2.5mm DC socket to 2.1mm. They are also listed by Kenable (Part No. 005013) for just 59p. However, I found these DC plugs to be a pretty slack interference fit that could pull apart again without much effort – something to bear in mind.

As the 'input' side of the splitter cable is 2.1mm, the spring-contact of the iPower-H supply lead connected to it very securely. It also plugged directly into the modem's 2.1mm DC jack, and finally the router and modem were both running from the mini 12V UPS, see photos.

I would expect the router and modem to continue for at least 30 minutes or so during power failures, enough to hopefully guard against brief power outages, surges and brownouts. An extra benefit is that the router's settings are preserved for a time, which can only reduce network disruption once mains power is restored again. If you know the load's power consumption, try using the 'Runtime' graph on the maker's online data sheet, see: **https://bit.ly/pe-dec23-iph**

On the threshold

My network also uses a 4-port Ethernet switch and a Wi-Fi mesh hub, which use 9V mains adaptors. Power Inspired offers an unusual uninterruptible power supply in the shape of a powerbank-style unit that can provide 9, 12 or 24V DC during



The writer's 12V router and modem; note the 12V DC splitter cable and 2.5mm adaptor on the router (left).

Sat on the floor, the author's iPower-DC² UPS underneath a 9V switch and 9V mesh hub (white cube) powered by the iPower-DC².

power interruptions. The iPower-DC2 is a compact 30W UPS with 10,000mAh internal battery and apart from a 5V, 10W USB power port there are no less than five DC jacks wired in parallel, their output voltage being pre-set by a single slide switch when the unit is offline. A row of LEDs indicates battery capacity, and a tri-colour LED denotes the set voltage.

The makers claim it provides at least 30 minutes runtime at full load, and over six hours at five watts. The one proviso is that it must be powered from a regulated mains power supply with a DC voltage that matches the UPS output (eg, use a 9V mains adaptor for 9V loads). The company tells me that the unit has a 'pass through' threshold voltage and that, as well as the different voltages, the input voltage has to be monitored closely. They explain that if the DC input was 10.5V, say, is that a 'low' 12V or a 'high' 9V? For safety the unit doesn't operate unless the input voltage is within tolerance of the selected output voltage, otherwise the Fault warning LED lights and the device shuts down. They state that any regulated mains PSU should be sufficient though – the unit needs a 36W supply at most, as the maximum output is 30W and the UPS consumes a further 6W. A Zolt PSU would suffice for 9V or 12V loads, or you can try the DC adaptor supplied with your apparatus. A DIN rail bracket is also available for secure mounting.

Personally, I haven't seen DC jacks being used as *outputs* before, and to use them a male-male DC lead is therefore needed. A pair of very short DC leads (5.5 x 2.1mm only) was included, though Kenable offers them in longer lengths for the CCTV market, along with handy DC extension leads.

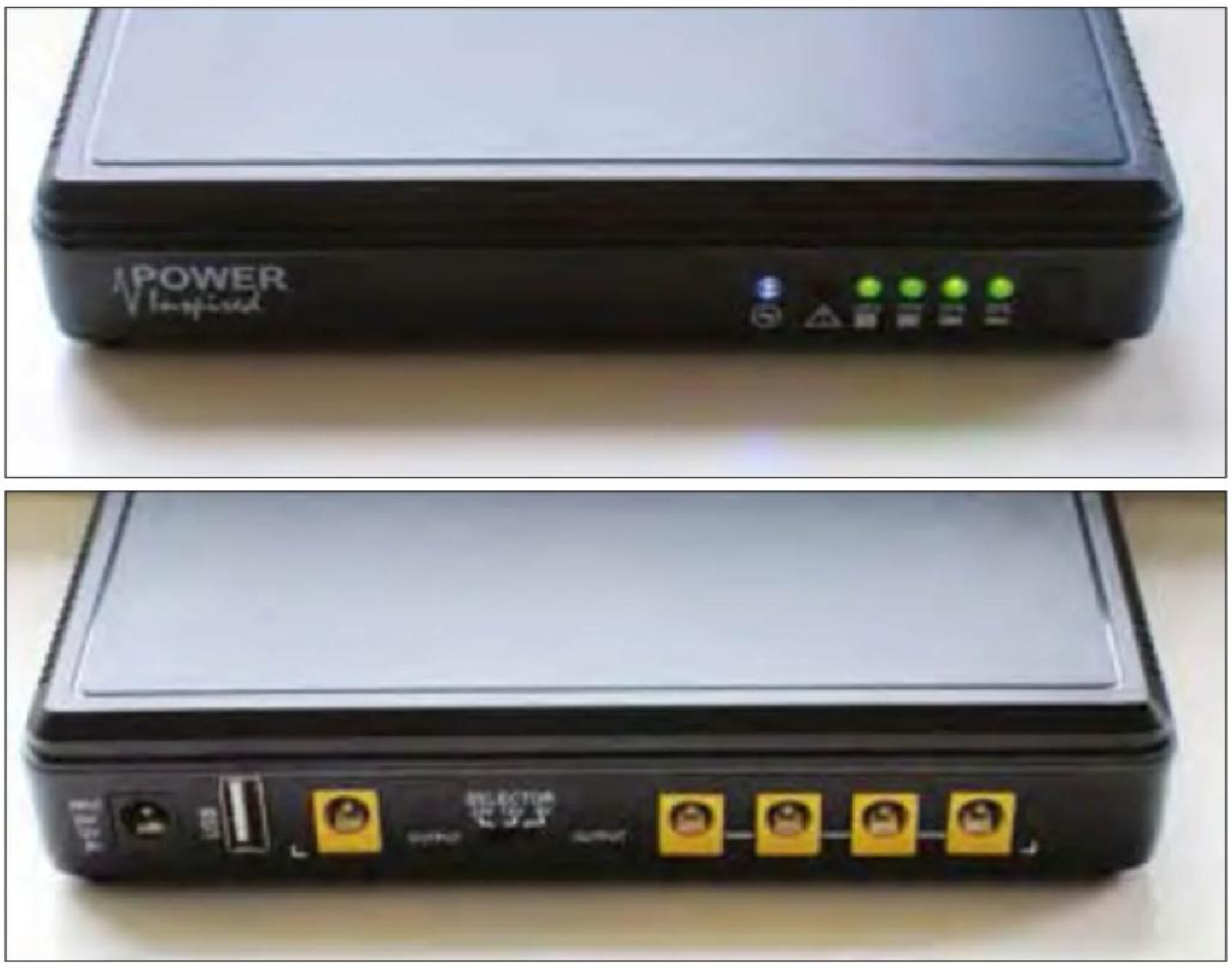
Unusual male-male DC leads are needed to connect loads to the UPS. A very short pair is included in the kit, others are available online.

I spent quite some time trying out the iPower-DC^2 using a Zolt 9V adaptor, connecting my network switch and mesh hub using the male-male leads provided. The battery UPS starts automatically when plugged into the mains, but it can only be switched off when in battery mode – ie, with the input fully disconnected. It took many hours for the internal battery to charge to 100%, and the output voltage cannot be changed while in use or the Fault LED lights and it shuts down.

After an awful lot of testing and some mild abuse I did on one occasion manage to lock up the UPS, which was overcome by disconnecting the internal battery for an hour to reset the microcontroller. I haven't seen the problem again, though the makers say it can also be soft-reset by powering off the unit and shorting any DC jack. Otherwise the UPS has operated as expected. The built-in USB port might be handy for powering some smart devices or a smartphone too.

Only time can tell how well the products will perform in practice, but they have freed up a couple of mains sockets and their unique compact design may well appeal to users looking to add extra protection to their home network, especially if power cuts are a nuisance. These versatile uninterruptible power supplies can be bought online direct from the manufacturers at: **https://bit.ly/pe-dec23-ups**

Other compact UPS products on the market include the Eaton 3S Mini UPS rated at 36W, which offers 9, 12, 15 or 19V DC priced at roughly £60, or the 12V Salicru SPS Net for the same price. Compare battery capacities as well.



The iPower-DC^2 is a powerbank-style compact UPS with five parallel 9, 12 or 24V DC outputs and a 5V USB socket.

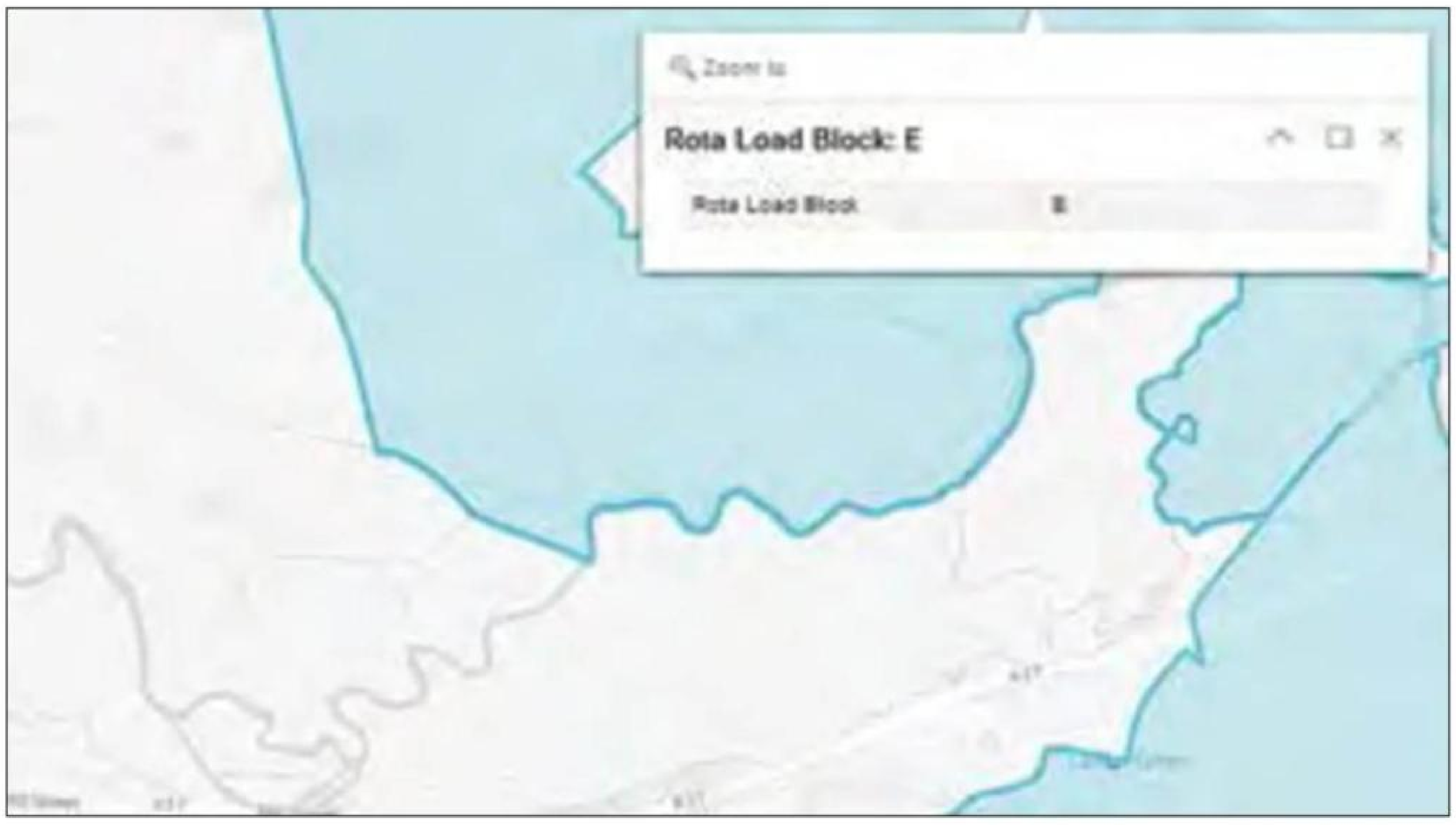
Caught in a Load Block

Still on the topic of power outages, regular readers will know that I'm currently kept busy down on the farm, in a rural area where smart meters are just a dream, but mains power cuts can be a nightmare. Strangely, the farm sometimes suffers a power cut along with some neighbouring villages, even though other areas, such as one half of the rural village in which I live close by, might escape cut-free. Why some areas can be hit while others are unaffected is explained by the electricity industry's use of 'power blocks' or 'Rota Load Blocks' which organise electricity distribution into blocks denoted by a letter (often seen on your electricity bill). It turns out that I'm located in a different block from the farm's, which for some reason is out on a limb and attached to a neighbouring block instead (probably to do with overhead cables).

It might be useful to know how power blocks are mapped out in your locality, which can be done by entering your postcode into **www.powercut105.com/en/**

In the UK, '105' is the phone number to report power cuts or obtain updates. However, I've found that by entering a nonsense postcode, the 105 web page offered a link to a more useful interactive map instead. Use it to search the correct postcode and one's location can be highlighted along with its Rota Load Block letter. This works best on a desktop PC, as you can zoom or click around to show neighbouring blocks. I found my own village is bisected by two blocks, hence one half can sometimes have a blackout while the other half is unaffected.

Rota Load Blocks are instrumental in managing power during civil emergencies or supply shortages, something we have fortunately not seen in Britain since the 1970s. How the UK Government would manage our electricity supplies at critical times is explained in a PDF in the rather dystopian Electricity Supply Emergency Code (ESEC) – see: **https://tinyurl.com/yrxxxsne**



Zoom to

Rota Load Block: E

Rota Load Block E

The 105 website for UK users shows your electricity Rota Load Block letter – to launch the map, search for a dummy postcode first. Neighbouring blocks can also be selected.

Just to cheer us all up, the Code's Annexes show the Block Disconnection Plan and Rotas of 3-hour power cuts that we hope will never be needed, especially the worst Level 18 Disconnection Plan (a total nationwide blackout). The National Grid has an outline at: **https://bit.ly/pe-dec23-disc**

A Quality job

I recently stumbled across an online ad by a firm that made 'smart' barriers that can be raised remotely to control traffic accessing, say, a driveway. A bright spark in marketing exclaimed that they had the 'ISO 9000 certificate for high-quality materials and exceptional manufacturing standards.' This irked me because, unfortunately for them, I happened to be an ISO9002 quality manager in industry at one time, so I immediately pointed out that their claims were meaningless!

Readers may often see 'ISO9000' certification mentioned in marketing material, but consumers should note that it has nothing to do with 'quality' as in Rolls-Royce, and therefore, it doesn't follow at all that you're buying the best 'quality' product. Instead, it means the product has been made to a documented, quality-assured standard or specification: the spec may say that propeller blades, for example, are made from balsa wood, but it will be a quality-assured balsa wood propeller rather than an aerospace alloy one.

The ISO standard evolved from the British car industry's efforts in the 1970s to raise quality by specifying, sampling and approving materials, suppliers and production. The famous British Standard BS5750 was the result, and it evolved into the internationally recognised ISO9000 standards. Importantly, it doesn't mean something is perfect either, but customer complaints get fed back into the system so that problems are gradually eradicated and products are refined over time. So, the next time you see an ISO9000 logo, remember that you're not necessarily buying a Rolls-Royce – it could be a lemon, but it will be a quality-assured lemon!

Chery picking

Still on the topic of vehicle quality, Chinese car manufacturer Chery has come out top in the 2023 JD Power *China Initial Quality Study*. British readers may not have heard of Chery, but they soon will, as it's reported they will arrive in the UK this year marketing a new 'Omoda' brand. Chery are also building four more factories in Asia and Argentina to build petrol, hybrid and electric SUVs. You can take a sneak peek at the forthcoming Omoda 5 SUV at: **https://bit.ly/pe-dec23-omoda**

Meantime, the cost of insuring Tesla and other electric vehicles has hit the crash barrier in Britain, as insurers recoil from the extreme costs of repairing them. The batteries effectively form the car's floorpan and repairs can be highly complex and ruinously expensive. Insurer John Lewis had suspended offering policies and Tesla owners were reportedly quoted £4,500 a year to renew – with some underwriters not renewing EV policies at all. Local authorities are also assessing whether multi-storey car parks can cope with the substantial extra weight of electric vehicles; a 1960s 'Brutalist' style multi-storey car park in the author's locality was refurbished at great expense but then had to be pulled down because structural problems made it unsafe for use.

Space news

Amazon has finally launched the first two satellites as part of its Project Kuiper programme. The test satellites were carried into LEO (low earth orbit) by a United Launch Alliance rocket in early October, and are intended to test telemetry of the satellites and ground network.

UK-headquartered OneWeb, a smaller rival to Elon Musk's Starlink LEO satcoms

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Registered
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An ISO9001 (or ISO9002) logo indicates that a quality management system to ISO standards is in place, but consumers should note it's no guarantee of 'Rolls-Royce' levels of quality. (Image: NQA)

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Amazon's Project Kuiper satellite broadband project saw two satellites launched in October for test purposes.

network, is merging with satellite operator Eutelsat. The newly formed Eutelsat Group will therefore be able to offer both geostationary earth orbit (GEO) and LEO-based space communications, including maritime, broadcast, inflight and satellite broadband services.

OneWeb was rescued from bankruptcy by the British Government and Indian telco Bharti Airtel in 2020, and it's since been reported that Britain's MI5 security service investigated a Chinese plot to acquire OneWeb for themselves at the time. The idea of using OneWeb in a new British satnav network was eventually shelved. There has been no news since 2021 about the UK's proposed Space-Based Positioning, Navigation and Timing (PNT) Programme, which has been floated as a replacement for GPS-based satnav systems. A satellite (the DOVER Pathfinder) intended to evaluate PNT technologies, was onboard the ill-fated Virgin Orbit 747 flight from Cornwall at the beginning of this year (see *Net Work*, Feb. 2023).

Online news

Amazon Prime customers will start to see limited advertisements on their streaming Prime Video channels starting next year. An ad-free option will cost an extra $2.99 or equivalent, in an effort to drum up more revenue. Of course, the current £8.99 monthly fee offers them some slack to raise prices up to the £9.99 price point, which I guess will follow next.

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If you're thinking of investing in any of Google's smart devices or Nest security hardware, a post on Android Authority might make you think twice. It summarises neatly many of Google's false dawns, failures and withdrawn products, and can be read at: **https://bit.ly/pe-dec23-googfail**

Facebook might sometimes have a lot to answer for, but it also has some positive uses: in the author's locality a distraught motor caravan owner posted a message saying that their pride and joy had been stolen from their driveway during the night. He reported it to the Police as usual, but he also posted an appeal and photos of the vehicle in a local Facebook group. A few days later an eagle-eyed Facebook user in a town 20 miles away spotted the camper van sticking out like a sore thumb in a housing estate, and he managed to re-unite it with its owner. Car thieves often park up for a few days somewhere to see if a tracker is fitted, and one motorhome owner suggested that a small tracker unit could be hidden in, say, a cushion. (Beware of cheap GPS trackers sold on the web that are tricky to set up and may depend on now-obsolete mobile data networks.)

At the same time, while I was checking through another local Facebook group, a car owner posted a photo of his classic car that he takes to car shows. I recognised it immediately as the Opel saloon that my father bought brand new in 1976, which I drove to nightschool as a teenager soon after passing my driving test (no pressure!). I learned the car would be exhibited locally in a few days, so I had the great pleasure of being re-united with our family car, now 47 years old and looking well with 151,000 miles on the clock. It's a funny old world!

That's all for this month. Don't forget, at our advert-free website – **electronpublishing.com** – you will find all the above links ready-made for you on the *Net Work* blog.

The author can be reached at:
alan@epemag.net

The **Fox** Report

Barry Fox's technology column

Too cheap to be true?

In last month's column I suggested replacing the 'old-fashioned' mechanical spinner HDD (hard disk drive) in a computer with a 'new-fashioned' SSD (solid-state drive), as a relatively simple way to radically improve overall performance. I added a few caveats, notably the warning that scammers are using online sales sites to offer fake high-capacity (mainly 1TB) SSDs at surprisingly low prices. Now is the time to flesh out this warning.

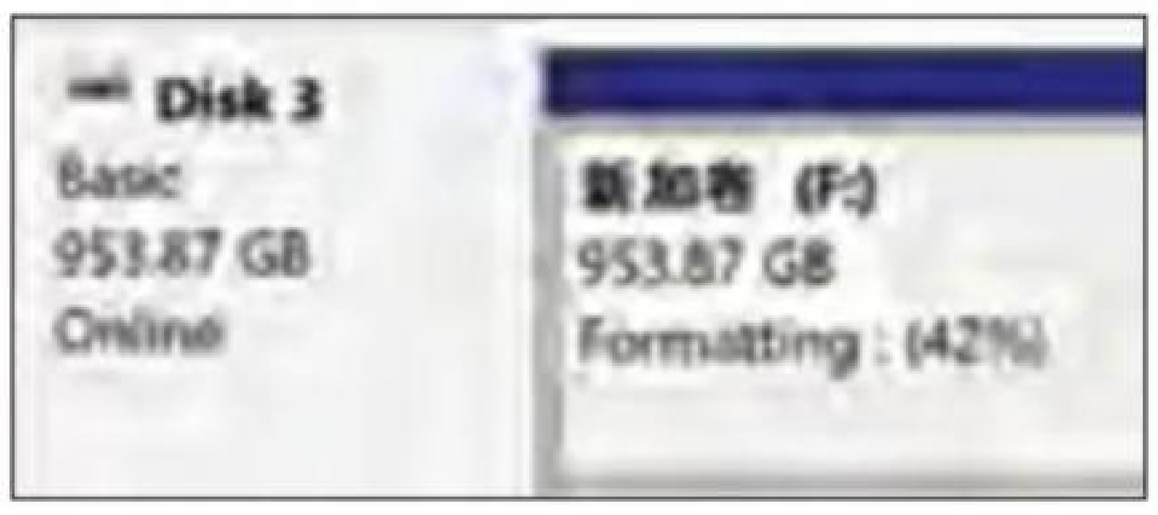
Scam drives

The fake capacity scam follows on from the scam sale, which began several years ago, of phoney USB memory sticks and portable USB HDDs. Fortunately, there are some easy, and free, ways to spot the phonies.

Hard technical and historical facts are tough to tie down, but it seems that one or more clever factories in China have created a memory controller chip that gives a false reading for the memory cells it is controlling. The controller tells a computer that the memory capacity is 1TB when the actual memory chips can only store around one tenth of that. The controller also fools the ordinary formatting process. So, plugging suspect memory into a computer and even fully formatting the memory fakes the 1TB capacity. In use, data appears to write to the memory as intended. But once the amount of data exceeds the real memory capacity, new data simply over-writes what was previous written or disappears into a black hole.

Over recent years I have been sold fake capacity USB sticks, portable HDDs and now SSDs. I was lucky. I know enough about IT to check, return to the seller and get a full refund. Many people, especially IT innocents looking for a bargain, will probably never know the drives they bought have not been storing all the data they appeared to be storing. By the time they find out that some of their stored data has been lost, all hope of claiming a refund will be long gone. The seller will probably be long gone, too. Very likely some sellers do not even know they are selling fakes because they do not have the IT savvy to check what their supplier has supplied. Most customers will not discover the problem until they find they cannot access data stored months or years earlier. They may well then assume the data loss is due to user error, media ageing or accidental erasure.

Because many online sellers all sell basically the same products, albeit dressed up in different cosmetic packaging, and sometimes with counterfeited trusted names, the golden rule is to check real capacity immediately after purchase and before storing any data. Experience suggests that once someone who is knowingly, or unknowing, selling fake drives is confronted with a fact-based refund claim, they will not want to risk a dispute that exposes the scam.



Disk 3
Basic
953.87 GB
Online

新加卷 (F:)
953.87 GB
Formatting : (42%)

Full formatting of an SSD can take the best part of a day.

But… how do you check if even full formatting will not expose the scam?

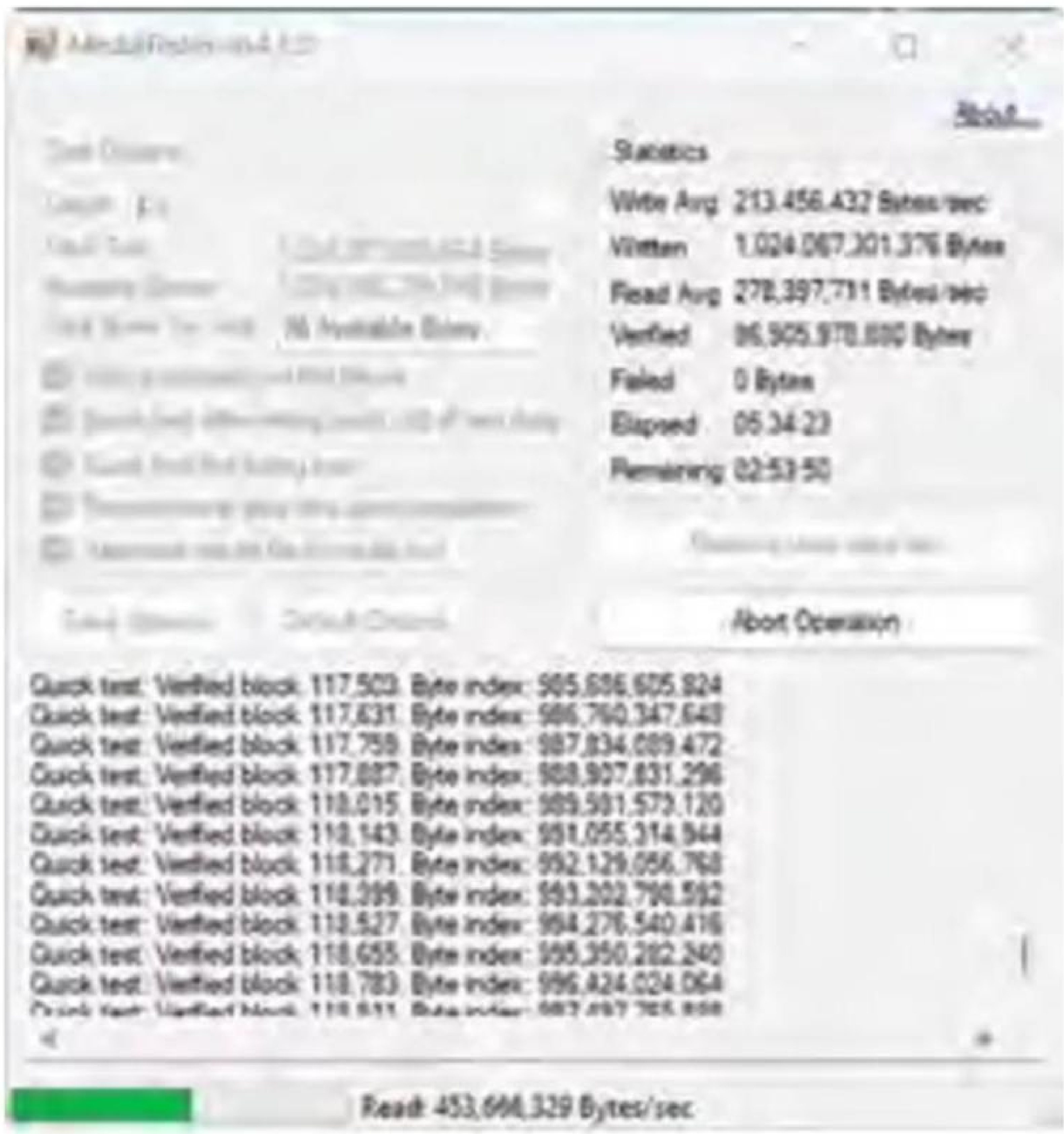
Is it a fake?

Fortunately, there are several capacity test apps available for free download. Take your pick from a web search but I opted for, and am recommending to others, the simple MediaTester. This is available as a standalone .exe file (no installation needed) from the Windows Online Store (which is in itself a good indication of safety), and also from Github:

https://bit.ly/pe-dec23-msmt
https://bit.ly/pe-dec23-ghmt

Software author Doug Krahmer says: 'Fake media sales have reached epidemic proportions. Fake media is being falsely labeled with popular brand names including SanDisk, Samsung, Sony, Kingston, and others. Not only are these counterfeit, but they often contain less storage than the cards report to the computer. A 128GB SD card may actually contain only 8GB or 4GB of actual space. After filling up all of the real space, the card will respond as if it is storing the data but it is actually throwing it away. The files will look like they exist but they are actually full of null bytes or completely corrupted. If you try to read the data you will find that it is ALL GONE.'

The screen grabs show a few readouts from MediaTester, captured while checking a range of SSDs. Most (bought from Amazon) passed the test because I paid a fair price for the capacity offered.; £17 for 256GB and £37

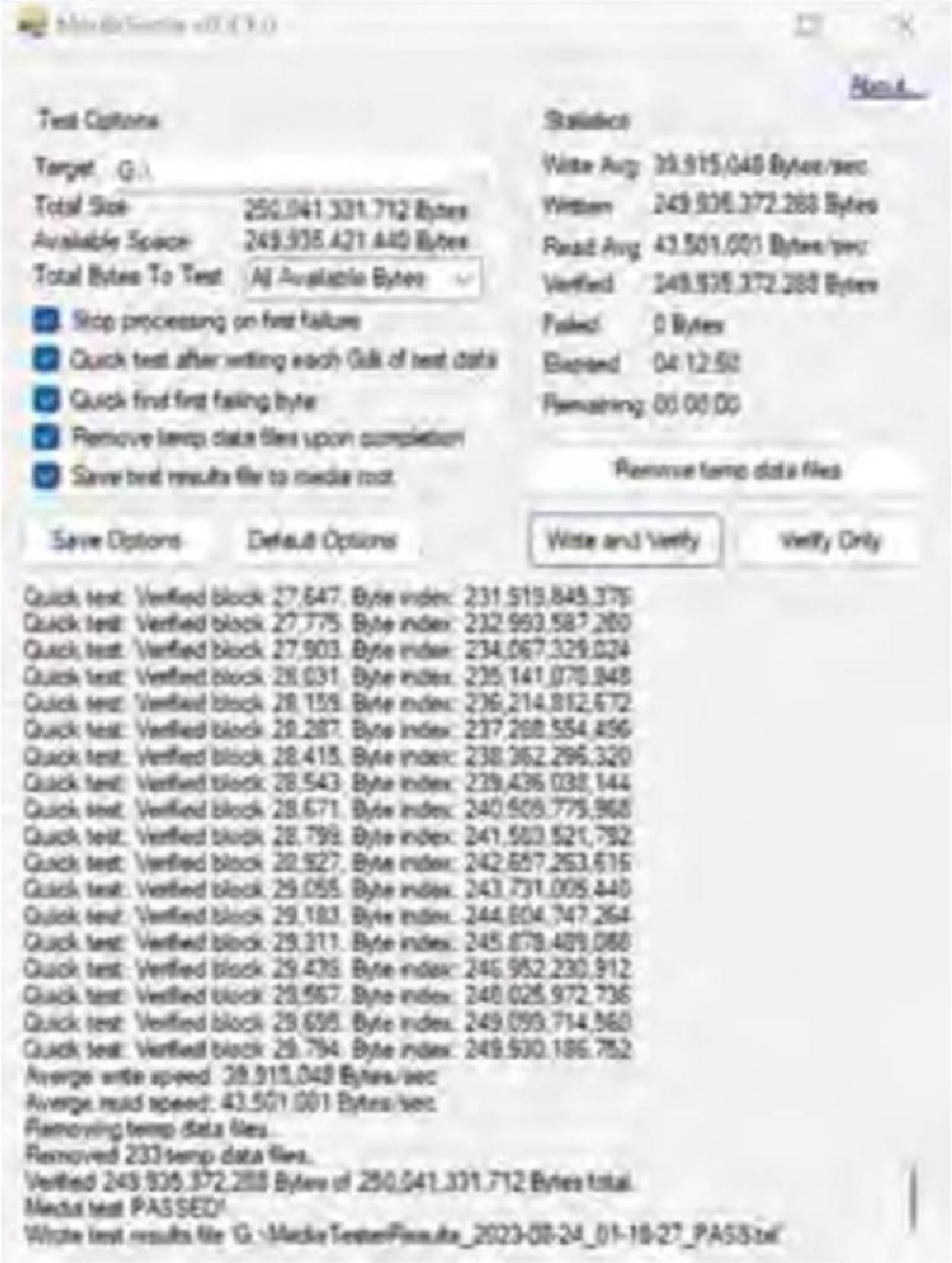


Statistics
Write Avg 213,456,432 Bytes/sec
Written 1,024,067,301,376 Bytes
Read Avg 278,397,711 Bytes/sec
Verified 96,505,978,880 Bytes
Failed 0 Bytes
Elapsed 05:34:23
Remaining 02:53:50

```
Quick test: Verified block 117,503 Byte index: 985,686,605,824
Quick test: Verified block 117,631 Byte index: 986,760,347,648
Quick test: Verified block 117,759 Byte index: 987,834,089,472
Quick test: Verified block 117,887 Byte index: 988,907,831,296
Quick test: Verified block 118,015 Byte index: 989,981,573,120
Quick test: Verified block 118,143 Byte index: 991,055,314,944
Quick test: Verified block 118,271 Byte index: 992,129,056,768
Quick test: Verified block 118,399 Byte index: 993,202,798,592
Quick test: Verified block 118,527 Byte index: 994,276,540,416
Quick test: Verified block 118,655 Byte index: 995,350,282,240
Quick test: Verified block 118,783 Byte index: 996,424,024,064
```

Read 453,666,329 Bytes/sec

Bliksem test moved on to reading and verifying.

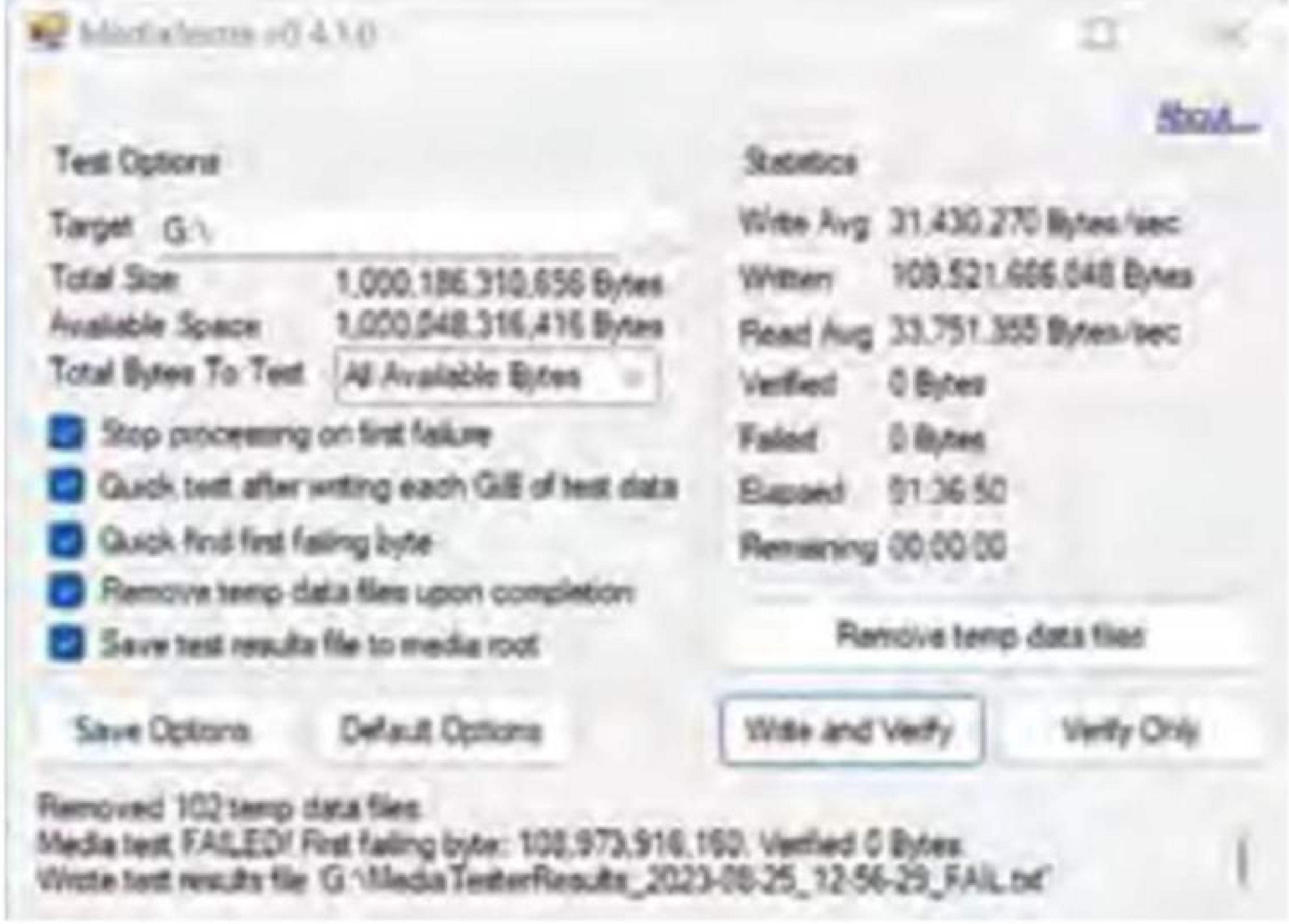


Target: G:\
Total Size: 250,041,331,712 Bytes
Available Space: 249,935,421,440 Bytes
Total Bytes To Test: All Available Bytes

☑ Stop processing on first failure
☑ Quick test after writing each GiB of test data
☑ Quick find first failing byte
☑ Remove temp data files upon completion
☑ Save test results file to media root

Write Avg: 39,915,048 Bytes/sec
Written: 249,935,372,288 Bytes
Read Avg: 43,501,001 Bytes/sec
Verified: 249,935,372,288 Bytes
Failed: 0 Bytes
Elapsed: 04:12:50
Remaining: 00:00:00

```
Quick test: Verified block 27,647. Byte index: 231,519,845,376
Quick test: Verified block 27,775. Byte index: 232,993,587,200
Quick test: Verified block 27,903. Byte index: 234,067,329,024
Quick test: Verified block 28,031. Byte index: 235,141,070,848
Quick test: Verified block 28,159. Byte index: 236,214,812,672
Quick test: Verified block 28,287. Byte index: 237,288,554,496
Quick test: Verified block 28,415. Byte index: 238,362,296,320
Quick test: Verified block 28,543. Byte index: 239,436,038,144
Quick test: Verified block 28,671. Byte index: 240,509,779,968
Quick test: Verified block 28,799. Byte index: 241,583,521,792
Quick test: Verified block 28,927. Byte index: 242,657,263,616
Quick test: Verified block 29,055. Byte index: 243,731,005,440
Quick test: Verified block 29,183. Byte index: 244,804,747,264
Quick test: Verified block 29,311. Byte index: 245,878,489,088
Quick test: Verified block 29,439. Byte index: 246,952,230,912
Quick test: Verified block 29,567. Byte index: 248,025,972,736
Quick test: Verified block 29,695. Byte index: 249,099,714,560
Quick test: Verified block 29,794. Byte index: 249,930,186,752
Averge write speed: 39,915,048 Bytes/sec
Averge read speed: 43,501,001 Bytes/sec
Removing temp data files...
Removed 233 temp data files.
Verified 249,935,372,288 Bytes of 250,041,331,712 Bytes total.
Media test PASSED!
Wrote test results file G:\MediaTesterResults_2023-08-24_01-18-27_PASS.txt
```



Target: G:\
Total Size: 1,000,186,310,656 Bytes
Available Space: 1,000,048,316,416 Bytes
Total Bytes To Test: All Available Bytes

☑ Stop processing on first failure
☑ Quick test after writing each GiB of test data
☑ Quick find first failing byte
☑ Remove temp data files upon completion
☑ Save test results file to media root

Write Avg: 31,430,270 Bytes/sec
Written: 109,521,666,048 Bytes
Read Avg: 33,751,355 Bytes/sec
Verified: 0 Bytes
Failed: 0 Bytes
Elapsed: 01:36:50
Remaining: 00:00:00

```
Removed 102 temp data files.
Media test FAILED! First failing byte: 108,973,916,160. Verified 0 Bytes.
Wrote test results file G:\MediaTesterResults_2023-08-25_12-56-29_FAIL.txt
```

(Left) MediaTester reports that a 256GB SSD, bought to use as the cache in a NAS, has passed the test.
(Above) MediaTester reports that a 1TB SSD quickly failed the test, even though it had been fully formatted, apparently, correctly. So I asked for and got a refund.

A fair low-priced 1TB SSD labelled Bliksem went through the day-long process of writing, reading and verifying – and Passed

for 1TB. The failure SSD was suspiciously cheap; 1TB for £18 from eBay. But it would obviously be dangerous to assume that just because an asking price is high, the product is legitimate. The seller may just be marking it up as a disguise.

Take your time

Be warned that fully checking an SSD can be very slow. A 1TB drive can take a day. One advantage of using MediaTester is that it runs a simple check before a full check, so phoney SSDs may fail after an hour or so, making a full check unnecessary.

If an SSD fails, make a screen capture of the fail note and append this to any claim for a refund. That way the claim is more likely to sail through. The eBay seller refunded my £18 with no quibbles. But with bare-faced cheek he asked me not to leave 'non-positive feedback'. Of course, I did, to warn others: **www.ebay.co.uk/itm/115852033293**

'The real capacity of this SSD was only around one tenth the 1TB claimed, as shown by routine Properties checks and formatting. I immediately asked for a refund and was immediately promised a refund. Similar cheap SSDs are widely on sale. I strongly suggest that anyone with one urgently checks it with the test software (such as the free MediaTest mentioned above). Although the SSD may appear to be storing data it may silently overwrite once the real capacity is exceeded.'

The fake I bought and returned is now listed as 'Out of Stock'.

OS cloning note

As a footnote tip, learned from successfully upgrading a Lenovo PC by replacing its HDD spinner with an SSD, Cloning the OS (operating system) direct from HDD to SSD may expose an annoying action by Windows; the PC may insist on assigning the SSD more than one Drive letter (eg, C: for the Windows OS and E: for the Windows Rescue partition). This problem may be solved by, instead of cloning the OS direct to the SSD from the HDD, making an image copy of the old HDD OS on an intermediary HDD and then restoring from this to the new SSD.

Yet another scam

Talking of clever scams, exploitation of a loophole in the lost password option offered by mobile (cell phone) networks, is escalating. One of my SIMs is O2 Pay as You Go, and I now get at least one call a week from scammers with foreign accents claiming to be from O2, and offering me a better deal on 'my contract'. The fact that I have no contract immediately flags the call as a scam, but others who do have contracts may well be suckered – especially because many companies now out-source their sales and support to Asia.

Sometimes I play along to confirm that the network has still not been able to plug the security loophole.

Briefly, here's how the scam works. The caller picks a mobile number at random or from harvested lists and hopes that (as in my case) it is still linked to the network that originally allocated the number.

After some flannel talk about service and deals on offer, the scammer says he/she will send a 6-digit security code to prove they are really from O2. The caller also says to ignore the security warning text which precedes the code. It's like the EULAs we never read.

Unbeknownst to the phone-owner the scammer has gone on line to the network website, while flannelling, and uses the called number to exploit the network's Lost Password/Password Reset facility. This is what sends the owner a security code.

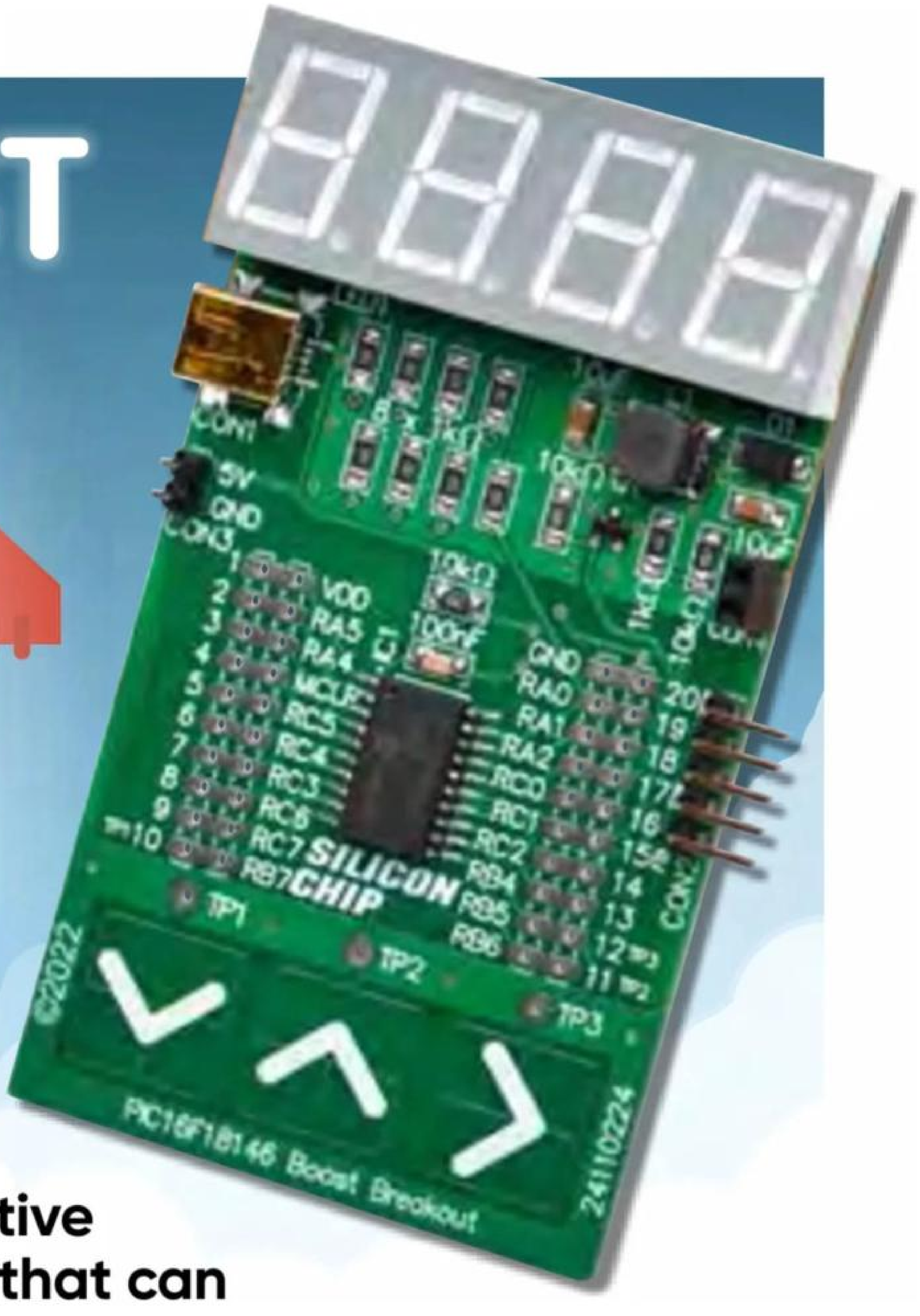
If the phone-owner falls for the trick and reads the code to the scammer, the scammer can immediately re-set the password, thereby locking out the rightful owner, and wreaking havoc, for instance using stored financial details to buy credit or order a new phone, and steal anything else available.

If I have a little time to spare, I sometimes waste the scammer's time by reading out wrong six-digit codes; I also ask for the address where they are working.

The last time this happened the scammer told he was at O2's HQ at 'Batherd, Slog, Birkshire'. He was of course reading Bath Rd, Slough, Berkshire from his scam script!

Digital Boost Regulator

By Tim Blythman



This board lets you use a PIC18F18146 8-bit microcontroller for any task while its onboard peripherals generate an adjustable voltage without interfering with what it's doing. It even includes some capacitive sense buttons and a seven-segment display that can be used to show the voltage or for other uses!

The PIC16F18146 micro has some interesting onboard peripherals. We realised it is possible to combine several of them with a small number of external parts to make a free-running, programmable boost voltage regulator that doesn't require any processor intervention while running.

This small PCB allows you to experiment with or use this concept. Since this 8-bit microcontroller has 20 pins, we've connected them all to headers for making off-board connections.

This design was prompted by our review of the latest 8-bit PICs in the October 2023 issue.

We've added a small LED display and some touch-sensitive pads to create a standalone, digitally controllable boost voltage regulator with a digital readout. If you're a keen programmer, you might be interested in testing your own designs using this chip. It could be used as the basis of all sorts of devices.

You could leave off most of the components and use the board to experiment with the bare chip, although we already presented a 'breakout board' that does that in the same October issue. Most recent 8-bit, 20-pin PIC microcontrollers have a similar pin layout, so this board could possibly be used with them too.

We purchased some PIC16F18146 chips in SOIC packages for this project and potentially for use in other projects. We chose that one over the others we looked at in October because it has more peripherals than the PIC16F18045, and importantly, it was available in a SOIC package (that isn't hard to solder).

The PIC16F17146 differs only in that it also has an internal op amp peripheral. That could be handy for some designs, but we shall have to see when stock becomes available to design a project around it.

The *Digital Boost Regulator* PCB suits all three of the aforementioned chips if you wish to experiment with them instead.

However, the other chips will need slightly different code to work, and we will leave that as an exercise for the reader.

The working principle of the boost circuit on this board is not novel. What is different is that instead of using a dedicated boost controller IC, we are simply configuring some of the PIC16F18146's internal peripherals to perform the same role.

Most dedicated switchmode controller ICs have more features, such as current limiting and short-circuit protection, that this design lacks. We have specified our circuit modestly to keep it simple.

Note that a dedicated chip will probably have a better control algorithm and thus tighter voltage regulation. While our design is not bulletproof, it is a working proof-of-concept that is usable in many roles.

This design is a way to show how valuable these advanced device peripherals can be. In particular, the configurable logic cells (CLCs) allow events to be responded to without requiring any processor attention.

We're only using a very small subset of the peripherals, so it won't

Features and Specifications

- Onboard digitally controllable boost (voltage step-up) converter from 5V up to 20V
- Output power of up to 0.5W (the output current depends on selected voltage)
- Capacitive touchpad interface
- Four-digit LED display
- Breaks out all microcontroller pins to headers

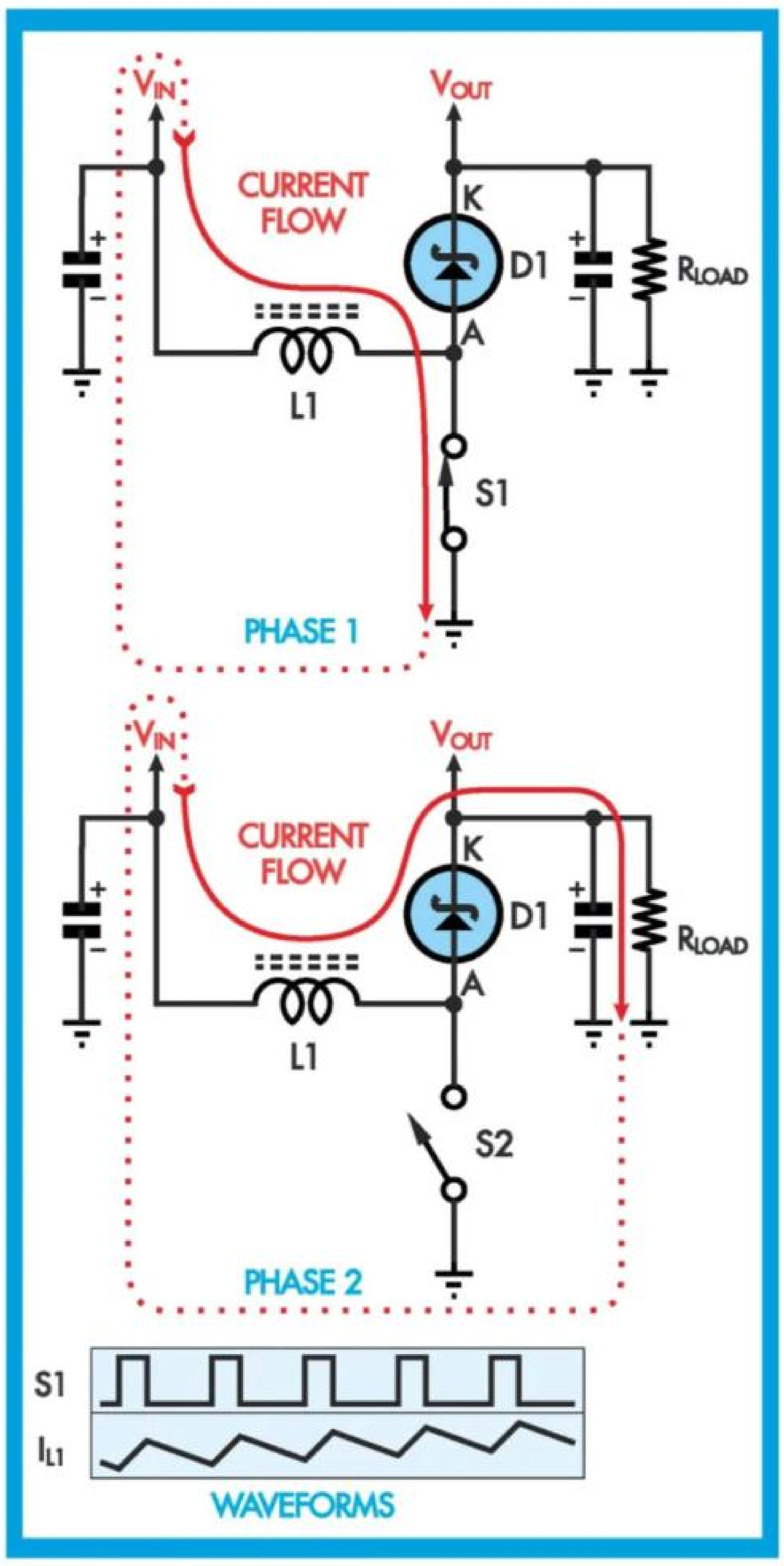


Fig.1: in a switched-inductor boost circuit, energy is stored in the inductor's magnetic field when current flows through it. As the magnetic field collapses, it drives current to the output via the diode. By changing the switch duty cycle, the average energy in the inductor can be changed, controlling the output voltage.

seriously impact the chip's ability to perform other tasks if you were to use it for the basis of a design. For example, the PIC16F18146 has two DACs and two comparators, but we only use one of each.

Boost regulator

Fig.1 shows the basic arrangement of the inductor-based boost circuit we are implementing.

If the switch is closed, as shown at the top of the diagram, current from the incoming supply flows through inductor L1 to ground, charging the inductor's magnetic field. When the switch opens, the inductor continues to pass current, but it is diverted via diode D1 to the capacitor and load on the right-hand side.

Consider the case when the switch stays open. Due to the diode drop, the output voltage settles just below the incoming supply. This is the minimum output voltage; such a circuit cannot deliver a voltage much lower than the incoming supply.

If the switch spends some of its time closed, the average inductor current is higher and thus, the output voltage increases. The theoretical maximum (disregarding efficiency factors such as resistance and voltage drops across the diode) is equal to the supply voltage divided by the switch's open duty cycle. So if the duty cycle is 50%, the voltage output is (in theory) double the input.

Theoretically, if the duty cycle drops to 10% open (which is the same as 90% closed), the output voltage will be ten times the input voltage. However, with such a high boost ratio, the peak inductor current becomes so high that the output deviates substantially from the theoretical voltage.

Circuit details

Fig.2 shows the full circuit of our *Digital Boost Regulator* and breakout board.

IC1 is the PIC16F18146 microcontroller with a 10kΩ resistor pulling its $\overline{\text{MCLR}}$ pin (pin 4) to its supply rail to prevent spurious resets. A 100nF supply bypass capacitor is provided for stable operation.

CON1 and CON2 are possible sources for the supply voltage. CON1 is a standard mini-USB socket with only its power pins connected. The circuit nominally runs on 5V and is perfectly happy with anything from 4.5V to 5.5V, as might come from a USB power supply.

CON2 is used to connect a programmer, such as a PICkit 4 or Snap, which can also supply power (the Snap requires a modification to do so).

Q1 performs the role of the switch from Fig.1; the 10kΩ resistor from its gate to ground holds it off when there is no signal from the microcontroller (eg, during programming).

A capacitor on the supply side of L1 provides a stable, local power supply for the boost circuit from the 5V rail. The output capacitor, downstream of the diode's cathode, is supplemented by a pair of resistors forming a voltage divider.

This allows the microcontroller to sense an output voltage that might be higher than it could otherwise accept. This divided voltage is taken to a pin on IC1 that can be configured as an input to the internal comparator. The divided voltage can also be sampled by the analogue-to-digital converter (ADC) peripheral, so we can measure the output voltage.

The output voltage on the capacitor is also taken to two-pin header CON4 so that you can feed it elsewhere.

TP1-TP3 are connected to PCB touch pads. They aren't external components but are formed from PCB traces designed to effect a change in capacitance when touched (the capacitors shown attached to the 'switches' represent the capacitance between the tracks). They each connect to an ADC-enabled pin of IC1. 17 of the 20 pins on the PIC16F18146 can be connected to the ADC.

Finally, LED1 is a four-digit seven-segment display connected to the remaining pins, configured as digital I/Os to drive the display in a multiplexed manner. Each of the eight segments (including the decimal point) has a series resistor for current limiting.

Firmware

Fig.3 shows how the internal peripheral blocks are configured to run the boost regulator.

Timer 1 is set running from the instruction clock. The comparator can be set to synchronise with this clock. We do this to prevent the comparator from oscillating at a high frequency when the output is near the setpoint.

The firmware also starts one of the PWM peripherals, set to operate at a 20% off and 80% on duty cycle. This puts a theoretical upper limit on the boost voltage that can be achieved, around five times the input voltage.

The PWM output is not sent to an I/O pin, but instead routed via an internal multiplexer to one of the CLC instances.

The FVR is set up to provide a 2.048V reference to one of the DACs (digital-to-analogue converters). The DAC is enabled and is internally connected to the non-inverting input of the comparator. The 8-bit DAC can thus apply a voltage from 0 to 2.040V in 8mV steps.

In practice, the FVR reference is not precisely 2.048V. The stated accuracy is 4%, but the factory measured value can be read from the chip's DIA (device information area).

With a 10:1 (10kΩ/1kΩ) divider, the output range is about 22.44V in 88mV steps. The upper limit of the boost circuit with an 80% duty cycle is around 25V, depending on the supply voltage. So we should be able to achieve 20V at the boost output easily, and that's what we've specified.

The inverting input of the comparator is connected to the divided output voltage. Being an analogue input, this can be one of four software-selectable pins. The comparator output is not exposed externally, although it could be. It is instead fed to one of the CLCs alongside the PWM signal.

The CLC is configured to simply provide a logical AND of the comparator output and the PWM signal. This is about the simplest possible application of the CLC.

The output of the CLC AND gate is fed to one of the I/O pins and thus to the gate of the MOSFET. Since it is a digital signal, we could map it to any one of the 17 I/O pins on the PIC16F18146.

At power-on, assuming the DAC output is set to a sufficient level, the divided output voltage is well below the DAC setting. So the comparator output is high, and the MOSFET drive signal follows the PWM signal.

When the voltage rises above the setpoint, the comparator output drops low, and the MOSFET drive is shut off until the voltage decays below the setpoint.

We can change the output voltage simply by altering the DAC value. So the processor does not need to spend any time handling the boost converter unless it wishes to change the settings.

The Timer 1 synchronisation takes care of any jitter that might occur around the comparator's switching point, preventing the MOSFET from trying to switch too frequently by synchronising its state changes to the timer.

While it might seem a simple exercise, this demonstrates just how useful and configurable the peripherals can be. For the sake of two external pins, an application circuit can make do without a separate boost controller chip and, as a bonus, have a programmable voltage setpoint!

Once the peripherals have been initialised, this part of the circuit continues to run without taking up any more processor cycles.

Scope 1 shows typical operation with an output voltage of around 8.5V, including the MOSFET gate drive and drain voltage. The broader peaks are complete PWM cycles, while the narrower peaks are when the PWM cycle has been interrupted by the comparator sensing that the voltage is above the programmed threshold.

A dedicated boost control IC would dynamically control the pulse widths and provide more uniformity, giving a smoother output, better regulation and better efficiency, hence our conservative ratings for our boost circuit. Still, it does the job of regulating the output at the target voltage.

Touch sensing

We've discussed the operation of shared-capacitance touch sensing previously, with quite a bit of detail in the *ATtiny816 Breakout Board* project (July 2021). The principle is that a finger brought near a touchpad

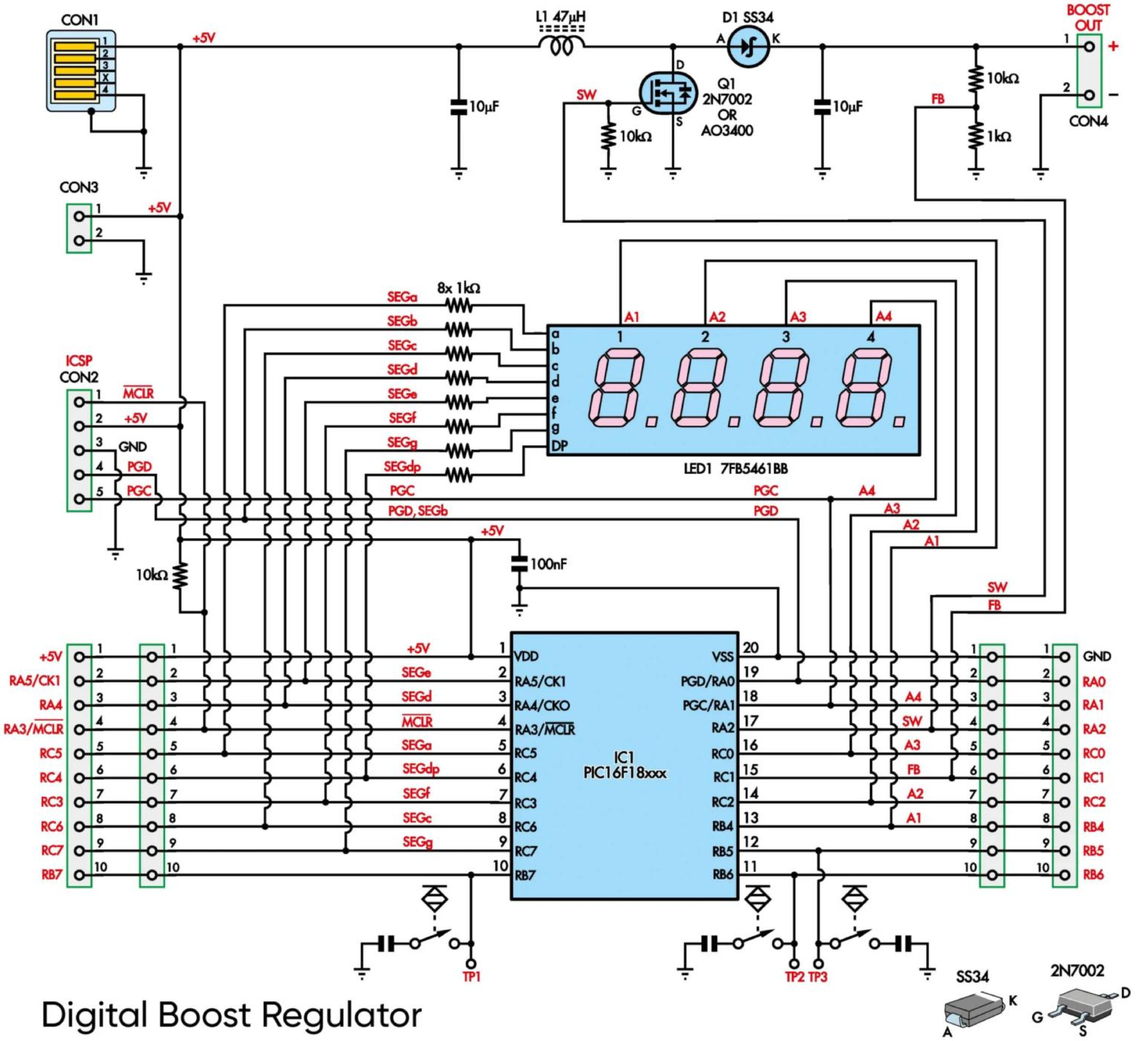

CON1
+5V
L1 47µH
D1 SS34
A
K
BOOST OUT
+
–
CON4
10µF
SW
D
G
S
Q1
2N7002
OR
AO3400
10kΩ
FB
1kΩ
CON3
8x 1kΩ
SEGa
SEGb
SEGc
SEGd
SEGe
SEGf
SEGg
SEGdp
A1
A2
A3
A4
LED1 7FB5461BB
ICSP
CON2
MCLR
GND
PGD
PGC
PGD, SEGb
100nF
IC1
PIC16F18xxx
VDD
RA5/CK1
RA4/CKO
RA3/MCLR
RC5
RC4
RC3
RC6
RC7
RB7
VSS
PGD/RA0
PGC/RA1
RA2
RC0
RC1
RC2
RB4
RB5
RB6
RA0
RA1
RB6
TP1
TP2
TP3
SS34
2N7002
Digital Boost Regulator

Fig.2: the lower section of the circuit shows the microcontroller connected to the rows of 'breakout' headers, along with the 7-segment LED display and the three touchpads. The boost circuitry at the top is driven by circuitry hidden inside IC1 (shown in Fig.3).

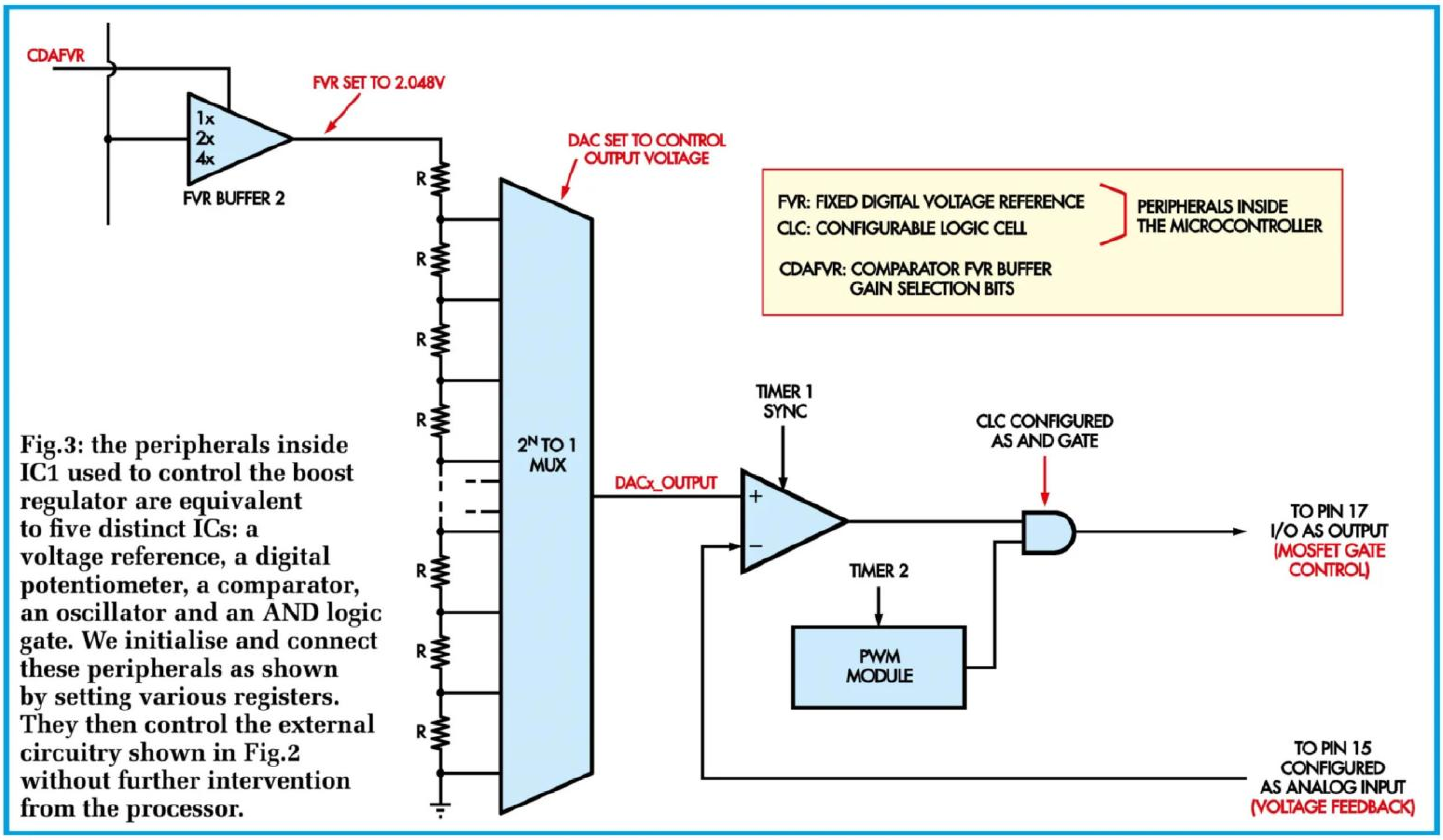

CDAFVR
FVR SET TO 2.048V
1x
2x
4x
FVR BUFFER 2
R
R
R
R
R
R
R
DAC SET TO CONTROL OUTPUT VOLTAGE
FVR: FIXED DIGITAL VOLTAGE REFERENCE
CLC: CONFIGURABLE LOGIC CELL
PERIPHERALS INSIDE THE MICROCONTROLLER
CDAFVR: COMPARATOR FVR BUFFER GAIN SELECTION BITS
2^N TO 1 MUX
DACx_OUTPUT
TIMER 1 SYNC
+
−
CLC CONFIGURED AS AND GATE
TO PIN 17 I/O AS OUTPUT (MOSFET GATE CONTROL)
TIMER 2
PWM MODULE
TO PIN 15 CONFIGURED AS ANALOG INPUT (VOLTAGE FEEDBACK)

Fig.3: the peripherals inside IC1 used to control the boost regulator are equivalent to five distinct ICs: a voltage reference, a digital potentiometer, a comparator, an oscillator and an AND logic gate. We initialise and connect these peripherals as shown by setting various registers. They then control the external circuitry shown in Fig.2 without further intervention from the processor.

increases its apparent capacitance and that change can be detected.

The PIC16F18146 microcontroller has an advanced ADCC or 'analogue-to-digital converter with computation'. It can perform multiple samples and provide computed results based on these samples.

One of the modes supports the measurement of a capacitive voltage divider, the same principle used in shared-capacitance touch sensing. Effectively, we are comparing the internal capacitance of the ADCC's sample capacitor (which the data sheet reports is around 28pF) to the capacitance of whatever is connected to the touchpad.

When a cycle is started, the ADCC performs a precharge step, which briefly connects the internal capacitor to the supply voltage and the external pad to ground (and vice versa). The internal capacitor and pad are connected together during the sample phase of the ADCC cycle.

The numerical result of the conversion depends on the relative capacitance values. Higher values correlate to a higher capacitance at the external pad, as it can hold and thus contribute more charge from the precharge cycle.

The PIC16F18146 can actually perform two measurements with inverted precharge polarities and report the difference. Once the ADCC is configured correctly, the channel (corresponding to one of the pads) is set, and the cycle starts. The result is read back a short while later.

Scope 2 shows the voltages on two touch pads during their cycles. You can see the two precharge and measurement steps for each pad.

While we could calculate the actual capacitance from the reading, it is simpler and sufficient to pick a threshold value that can distinguish between the presence or absence of a finger near the pad. A brief software routine scans the pads and sets the values in an array to whether or not a touch was detected on each pad.

The other job of the firmware is multiplexed driving of the 7-segment LED display. For this, a timer interrupt is set to trigger 240 times per second. The display is blanked at each interrupt, and the output pins are changed to display the next digit in turn.

As it is a common-anode (CA) display, one of the four anodes is pulled high, while the remainder are left floating. Any segments to be lit on that digit are pulled low. The 60Hz update rate combined with the persistence of vision makes the display appear steady.

After construction is complete, we'll discuss the actual use and operation of the default firmware.

Construction

The following assumes that you want to build the *Digital Boost Regulator* as described above. You could instead omit some parts and make a custom circuit by adding parts or connections to the breakout headers while using some or all of the included features.

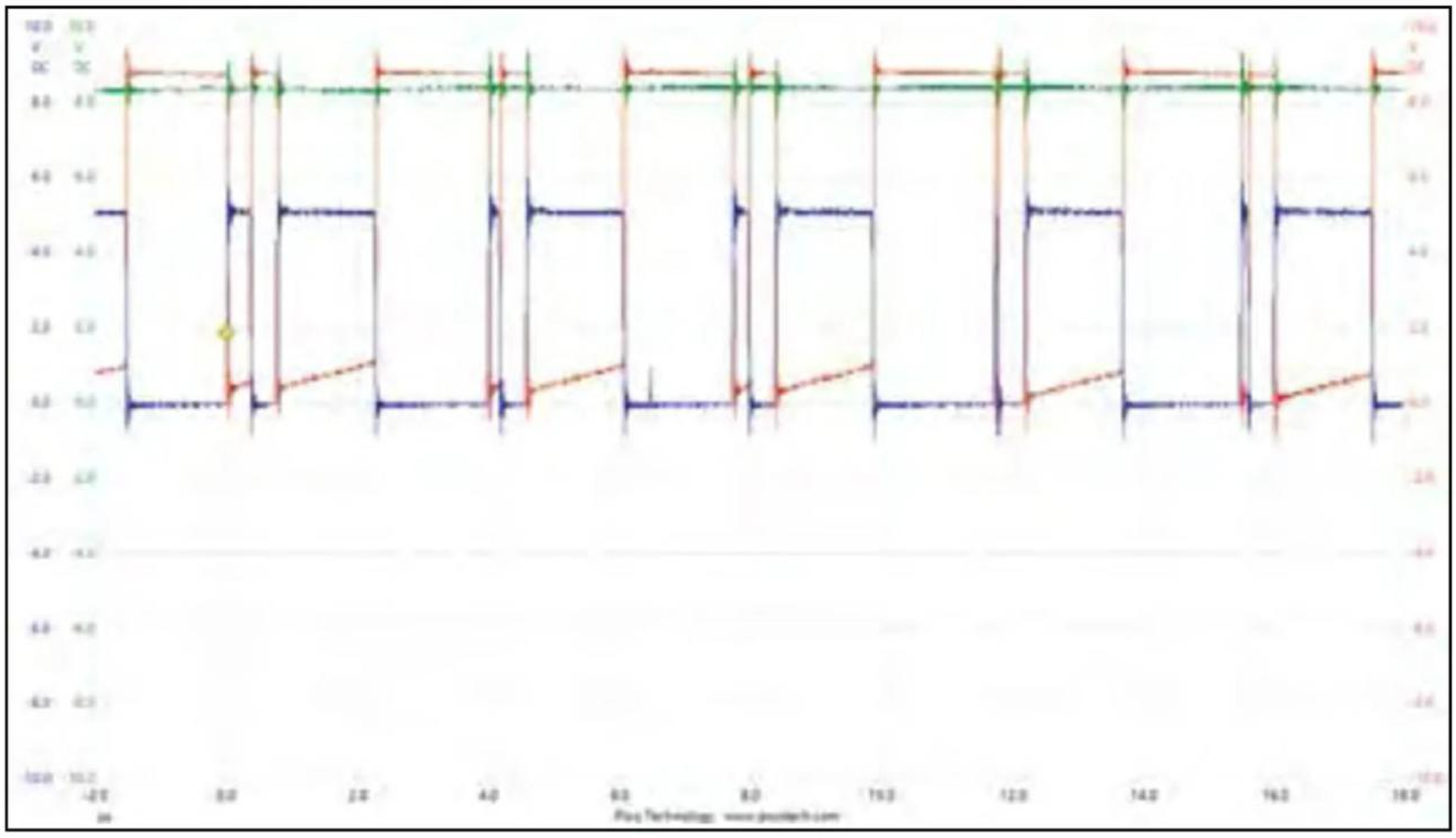
Parts List – Digital Boost Regulator

1 double-sided PCB coded 24110224, 50 × 89mm, available from the *PE PCB Service*
1 SMD mini USB socket (CON1)
1 5-way right-angle pin header (CON2; **optional**, for ICSP)
1 2-way pin header (CON3; **optional**)
1 2-way pin header or socket (CON4; **optional**)
1 47μH 1A 6×6mm inductor (L1) **[eg, Taiyo Yuden NR6045T470M]**

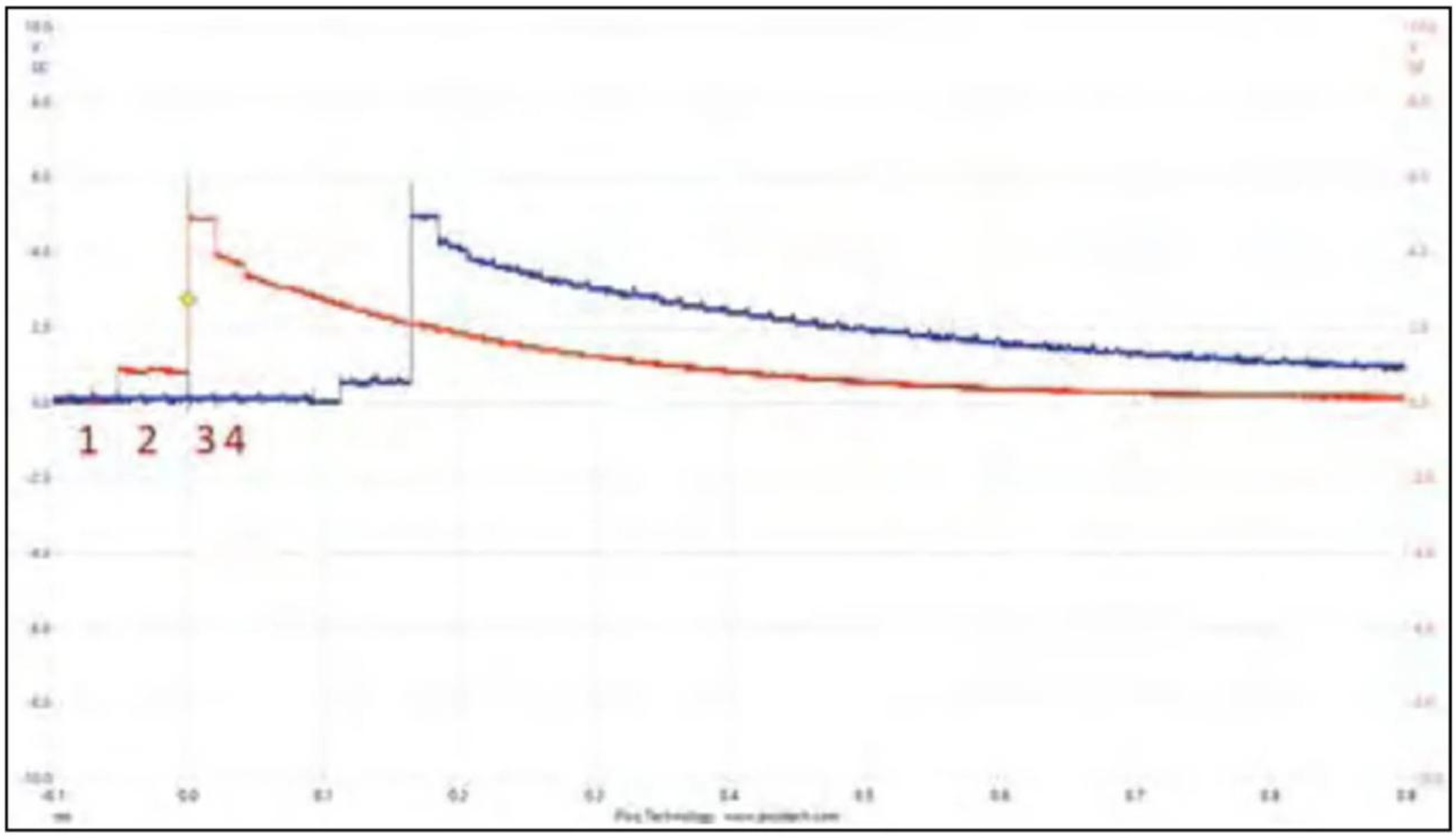
Semiconductors
1 PIC16F18146-I/SO programmed with 2411022A.HEX, wide SOIC-20 (IC1)
1 14mm/0.56in blue common-anode 4-digit 7-segment LED display (LED1) **[eg, 7FB5461BB]**
1 SS34 or similar 40V 3A schottky diode, DO-214AB (D1)
1 2N7002P, 2N7002K or AO3400 N-channel MOSFET, SOT-23 (Q1)

Capacitors *(all SMD M3216/1206-size X7R ceramic)*
2 10μF 25V+ 1 100nF 50V

Resistors *(all SMD M3216/1206-size 1% ⅛W)*
3 10kΩ 9 1kΩ



Scope 1: the blue trace shows the signal from the microcontroller to drive the gate of Q1 while the boost circuit is delivering 8.5V under load (green trace). The red trace is the voltage at the anode of D1. Dedicated boost controller chips typically change their duty cycle dynamically to control the output, while this circuit uses a fixed duty cycle modulated to limit the voltage.



Scope 2: the voltages at the I/O pins for two touchpads during the ADCC sampling cycle. The period labelled '1' is precharge while '2' indicates sampling. '3' and '4' are the same phases but with a positive precharge. Note how the stage 2 and 4 levels for the blue trace are further apart than for the red trace; that pad is being touched, and it is that difference that the ADCC reports.

The *Digital Boost Regulator* and breakout board is built on a double-sided PCB coded 24110224 that measures 50 × 89mm and is avalable from the *PE PCB Service* (see Fig.4). It uses practically all surface-mounting parts, so you should have flux paste, tweezers, a magnifier, a fine-tipped iron and some solder-wicking braid on hand. The flux will generate smoke, so use fume extraction or work outside to avoid breathing it in.

Start by fitting USB socket CON1. Place flux on the pads, then rest the socket on top. This part has lugs that will locate it correctly, so alignment shouldn't be difficult.

Clean the iron tip and apply some fresh solder to it. Touch the iron to the small pads and allow the solder to flow onto them. Only the two longer pads need to be soldered. If you form a bridge, use the braid and extra flux to remove it. Then solder the four larger pads around the sides of the shell to secure it mechanically.

Apply flux to the pads on the PCB, then fit IC1. Rest it in place, tack one lead and confirm that it is flat and aligned with all the pins. Also ensure that the divot or notch marking pin 1 is at the upper left, as per the PCB silkscreen markings. When everything is aligned, solder the remaining pins.

Add some flux to the rest of the pads for the surface-mounting parts. Q1 is the only transistor and should be oriented as shown. The solitary diode (D1) must be aligned with its cathode stripe to the right. The remaining parts are not polarised.

Use the same technique of soldering one lead and checking that the part is correctly positioned before soldering the remaining leads.

The two 10µF capacitors are near L1 and D1, while the 100nF capacitor is above IC1. Fit these next, being careful not to mix them up as they won't have markings.

There are only two different resistor values, but take care not to mix them up. Most of the 1kΩ resistors are grouped together near CON1; these are the current-limiting resistors for the LED segments.

The last surface-mounting part is L1. Turn up your iron temperature a little, if possible, as this part has more thermal mass than the others. Add a thin layer of flux paste to its pads then, as for the smaller parts, tack one side, check the position and then solder the other leads.

Refresh any solder joints that look dry or rough by adding more flux and

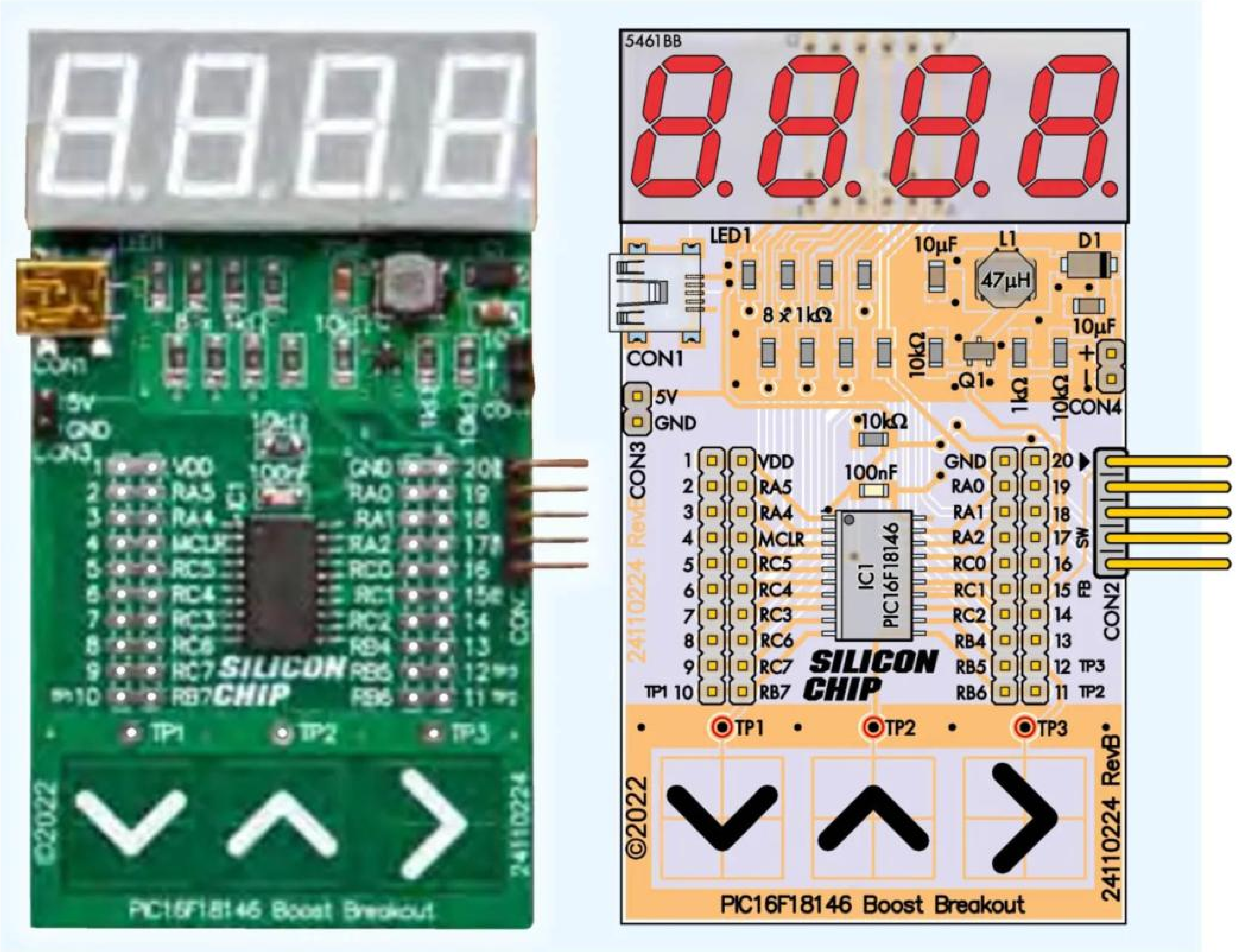


Fig.4: the Digital Boost Regulator mainly uses SMD parts, but they are all fairly easy to work with. Watch the orientation of the diode, IC1 and LED display, and you should have few problems. If you omit all parts except IC1 and its two adjacent passives, you can use the PCB as a breakout board that suits many recent 8-bit PICs in 20-pin SOIC packages.

touching a clean iron tip. The solder should flow and smooth out.

Before fitting the remaining through-hole parts, clean the PCB of excess flux using a recommended solvent and allow it to evaporate.

Then check the alignment of LED1, being sure to orient it as per our photos and overlays. Solder it from the back of the PCB and trim the leads close.

If you want to fit CON3 (for a 5V supply) or CON4 (to run the boosted voltage elsewhere), these can be header pins or sockets. If you like, you could add 10-way socket headers to the breakout pads to allow breadboard jumper wires to be used.

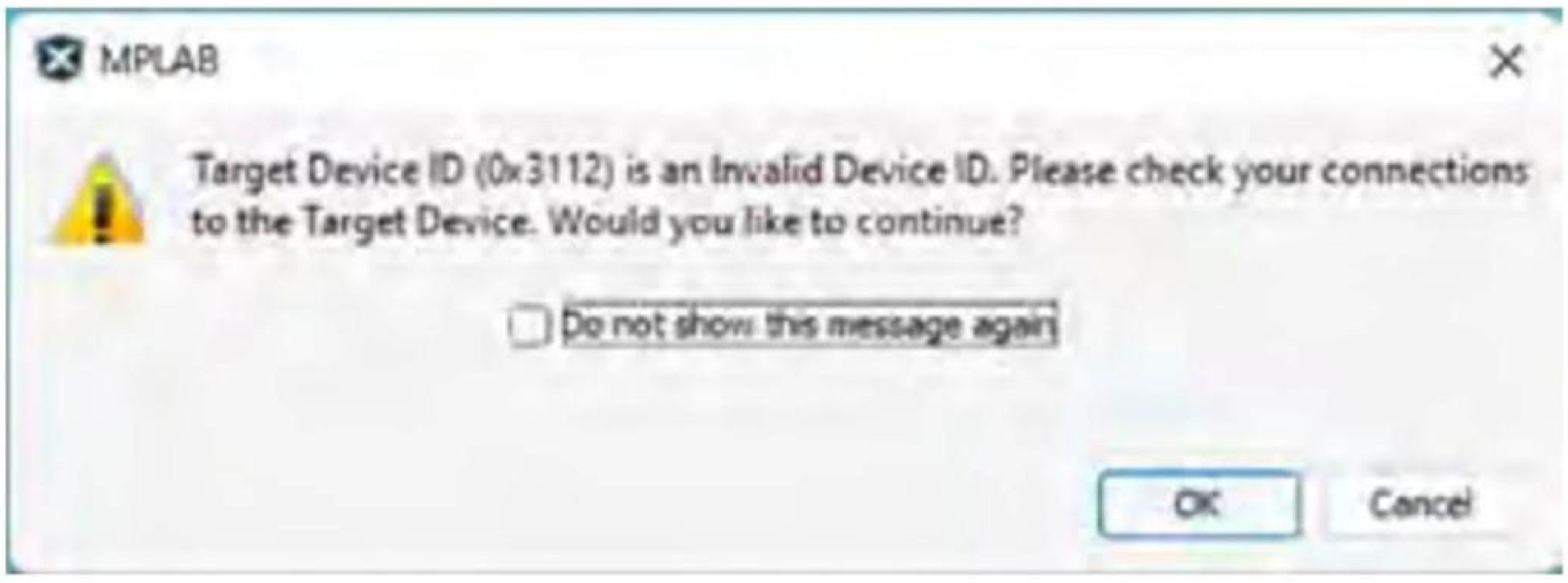
CON2 is only needed for in-circuit programming of IC1, so it can be omitted if you are working with a programmed chip, and don't plan to experiment with the code. A right-angled header is recommended if you do fit CON2.

Programming IC1

If this is necessary, you can use a PICkit 4 or Snap programmer. The Snap will require power to be supplied, which can come via CON1.

You will need a relatively recent version of the MPLAB X IDE or IPE and the PIC16F1xxxx device family pack (DFP). We're using MPLAB X v6.00. If you wish to experiment with the software, you'll also need the XC8 v2.40 compiler.

Although the programming pins are also used to drive the LED display, they don't interfere with programming. At worst, there is faint ghosting on the LED display when the programmer is connected. We didn't run into any problems with programming the chip after the board was complete, although it didn't seem possible to perform debugging.



Target Device ID (0x3112) is an Invalid Device ID. Please check your connections to the Target Device. Would you like to continue?

☐ Do not show this message again

Screen 1: if, during programming, you see an error message indicating that 0x3112 is an invalid device ID for the PIC16F18146, you can safely ignore it. The data sheet shows that 0x3112 is the correct ID.

Connect your programmer to CON2 and upload the **2411022A.HEX** file using the MPLAB X IPE. This HEX file is available from the December 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

We did run into one odd bug, and you might, too; the programming software reports that 0x3112 is an invalid device ID, even though the data sheet indicates that this is the correct device ID for the PIC16F18146. If you get the same error message with that exact value (see Screen 1), it is safe to ignore it.

You can continue to use the programmer to supply power, but the PICkit 4 cannot provide much current and won't be very useful for running the boost regulator. For that, you'll need to connect an external 5V supply, which could be as simple as a USB cable from a computer or charger.

Operation

Assuming you have a 5V supply connected, you should see the display reading around 4.70 (the units are always volts) with the rightmost decimal point also lit. You can connect a multimeter to CON4 to check the output voltage.

If the displayed or measured voltage is much higher than the input, there may be a problem, so you should shut down the *Digital Boost Regulator* and check the construction. The limited duty cycle should prevent the output from going way too high if there is a problem with the feedback system.

This default display shows the output voltage while the rightmost decimal point indicates that the boost circuit is enabled. If the supply voltage drops too low (below 4V), the output will switch off until the supply voltage increases above 4.5V.

As newly programmed, the boost circuit is enabled, but with a target of 0V, so the output voltage is simply the supply less the drop due to the diode.

Pressing and holding the > button under TP3 will cause the display to switch to the setpoint display and start flashing 0.00. You can change the setpoint by holding one of the up or down buttons while holding the > button. The change happens straight away.

Each step of the setpoint corresponds to one step of the DAC output. The displayed voltages are calculated based on the internal voltage reference values from the device information area, so the steps are not uniform (due to rounding) and the maximums might not align.

Still, you should have no trouble setting and achieving a 20V output.

Releasing the > button will return to the actual voltage output display. You should see the output tracking the setpoint as long as it is above 5V. The output will float a bit high with a light (or no) load as the boost circuit does not shut off until the output voltage is above the setpoint.

Pressing the up and down buttons together will display 'b' and the supply voltage.

Finally, if all three buttons are pressed simultaneously, all segments will flash on, and the setpoint is saved to EEPROM so that it is used by default at power-up. The safest way to do this is to hold the up and down buttons and then press the > button. That way, the setpoint can't change.

If all the segments don't light up, the saved value may be the same as setpoint, meaning it doesn't need to write to the EEPROM. If it did, that would cause extra write cycles (and wear) on the EEPROM.

If you find the *Digital Boost Regulator* is not responding to touches or is flashing when no touch pads are pressed, then be sure that you don't have anything connected to the touchpad I/O pins, especially circuitry that may affect the capacitances.

Code details

We tested our prototype with various power supplies, both grounded and ungrounded and chose our touch sensitivity values based on those tests. These are the TOUCH_DOWN and TOUCH_UP values near the top of the **io.h** file. Having two values allows us to provide some hysteresis and thus debounce the buttons.

Since the measured value increases on a touch, the sensitivity can be reduced by increasing these values. Conversely, the sensitivity can be increased by lowering the values. You shouldn't need to make any changes if you are using the board as designed, but if you try to make touchpads by running wires from TP1-TP3, then you may find that the capacitances change.

No doubt some people will be interested in using bits of our code, especially the boost and touch sections. So we've tried to make it modular and section the code into dedicated functions for each.

The doTouch() function calls several other functions to check the state of the touch pads and store them in the t[] array. The other functions include initADCcvd() and getADCcvd().

The boostInit() function sets up the peripherals used for the boost controller. Controlling it simply requires that the DAC is set using the DAC1DATL register after it is enabled by clearing the TRIS bit of the RA2 port pin (which has been defined as SWPIN).

Minimal circuitry

If you want to use the board as a breakout for the PIC16F18146, only the 100nF capacitor and 10kΩ resistor adjacent to IC1 are needed for operation. The LED display and its eight 1kΩ resistors can be omitted to free up 12 I/O pins.

Q1, L1, D1, CON4 and the associated passives, which include a 1kΩ, two 10kΩ resistors and two 10μF capacitors constitute the components that provide the boost feature. Leaving these off will free up two IO pins.

Naturally, you will need to change the code to work without the display, and if you need a further three I/O pins, you will need another control method to replace the touch pads. However, they can't easily be physically removed without sawing off the bottom section of the PCB.

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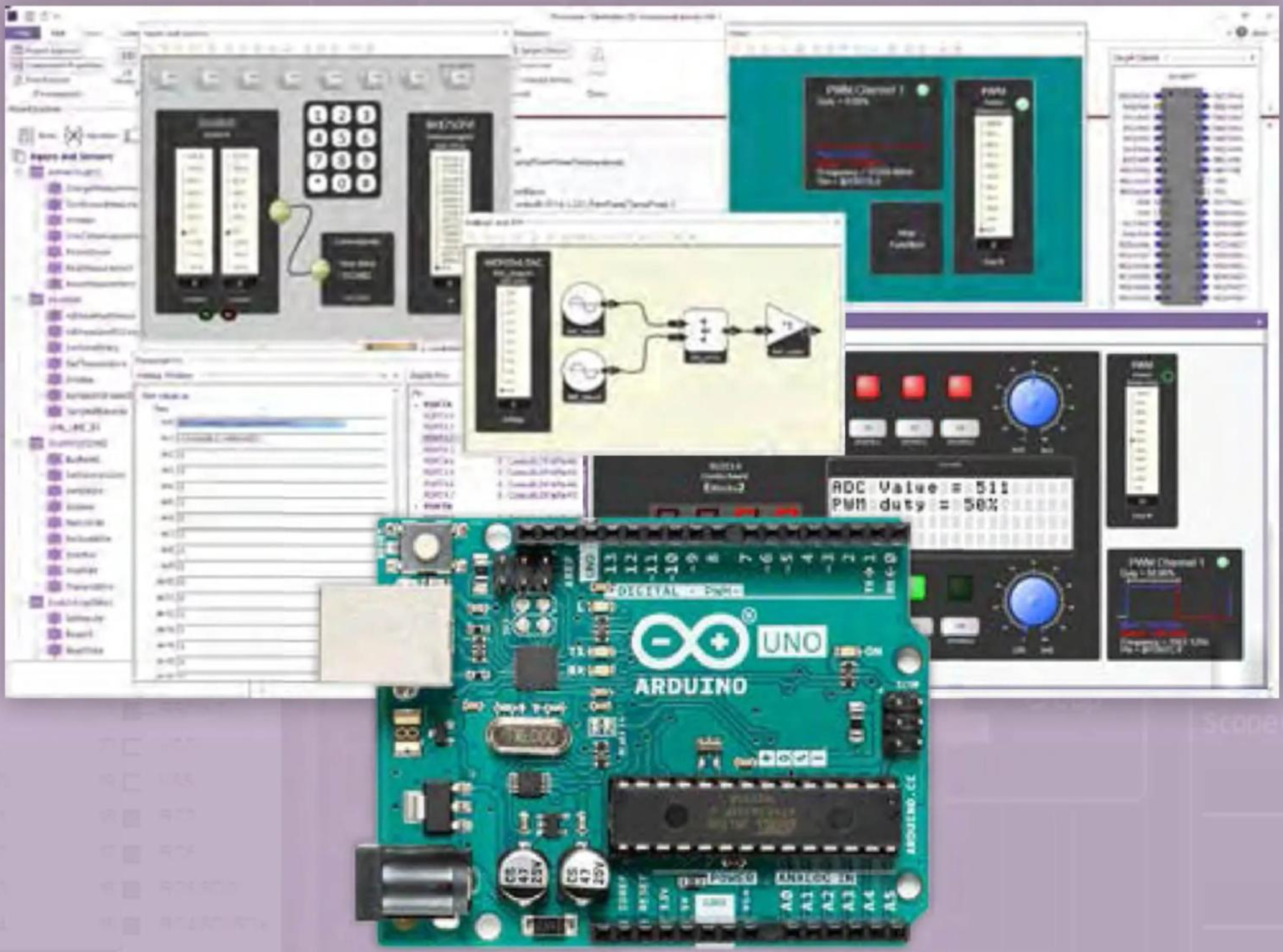
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S10.5v 0.06A 10.8v 0.77
A10.5v 0.00A 10.8v 0.01
0.0v 0.0v 0.0v 0.0v
0.00A 0.00A 12.0v

Tim Blythman's

Dual-Channel Power Supply for BREADBOARDS

Things can get messy when you're prototyping a design on a breadboard but you definitely don't want to make a mistake hooking up the power supply! This Dual-Channel Breadboard PSU is the perfect solution. It plugs straight into a breadboard's power rails, has two adjustable current-limited outputs and can run from different power sources. It has already become an indispensable part of our workbench.

We do a lot of prototyping on breadboards. It's the easiest way to test ideas, especially if you need to try out tweaks and modify a circuit configuration. Jumper wires make it nice and easy to wire up a circuit and make changes on a solderless breadboard.

While you can get compact power supply modules that plug straight into a breadboard and provide 5V and 3.3V rails, like Jaycar Cat XC4606 and Altronics Cat Z6355, they have their drawbacks. The main problems are that they only offer one voltage at a time and lack the flexibility and current-limiting features of a bench power supply.

So we decided to design a low-cost, easy-to-build replacement incorporating the most important features of a bench supply.

The result is a Breadboard PSU that's versatile yet straightforward. It plugs directly into a breadboard's power rails at one end, like the simpler supplies described above, but it has two independent outputs.

We have published a similar design called the Arduino-based Power Supply (February 2022), a compact solution for a home workshop. Like this Breadboard PSU, it provides up to 14V output at up to 1A, although it only has one output.

As the Arduino-based Power Supply is controlled by a computer, it can be tucked away. Its controls and display are displayed on the computer screen, so it does not take up any more valuable workbench space.

But there is nothing quite so tactile as being able to adjust a couple of knobs to dial in voltage and current settings while you're testing a prototype, and that is how the Breadboard PSU works. If you're working close-up with the breadboard, having the supply controls nearby is convenient, and the PSU doesn't make the whole breadboard set-up much bigger.

Two independent output channels

Most breadboards have at least two sets of supply rails, one pair on either side. Given that, and the fact that many circuits require two voltages (eg, 3.3V and 5V or 5V and 12V), adding a second channel seemed like a great idea.

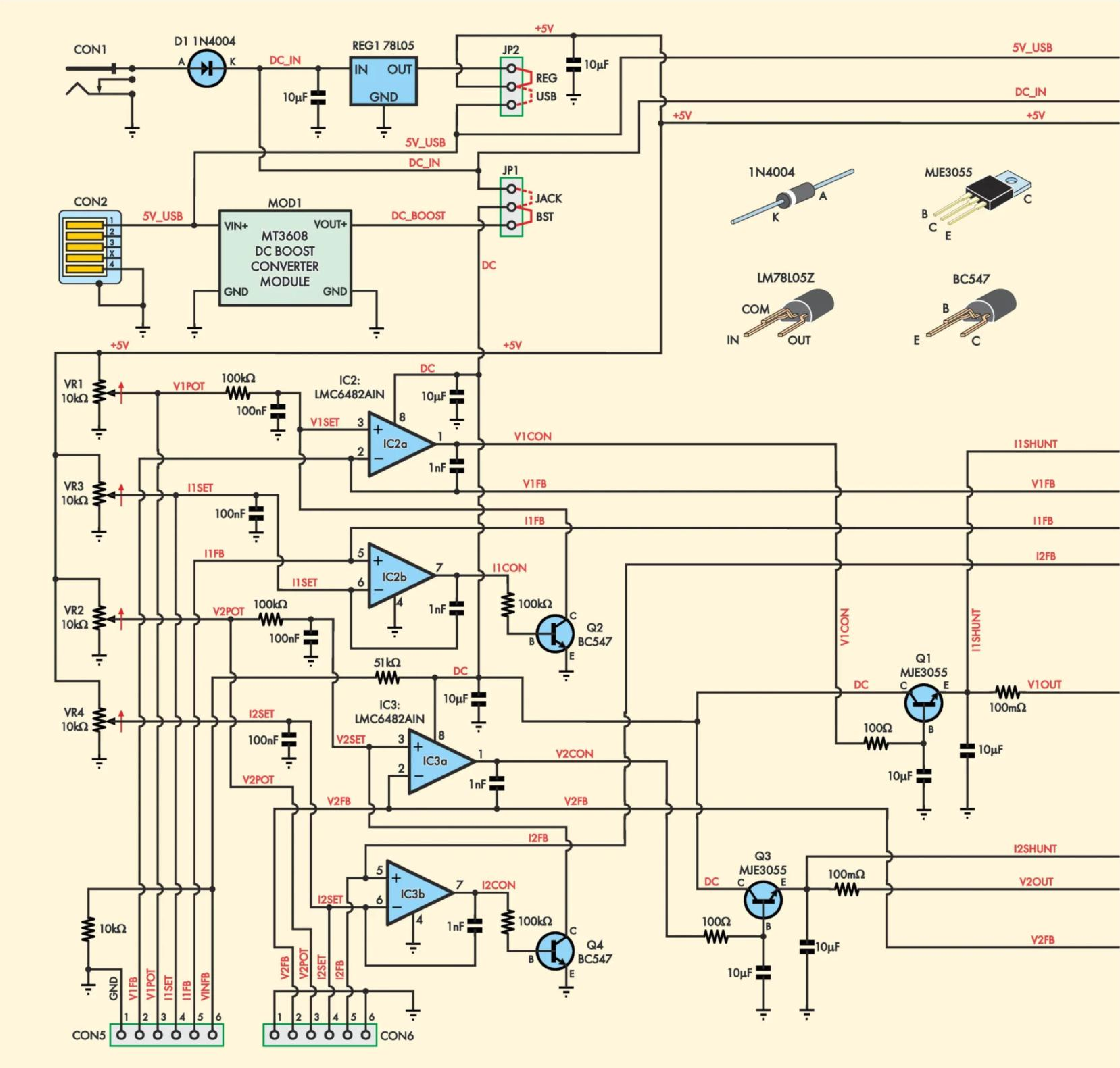
Even just using the two outputs as independent, current-limited supplies at the same voltage can be very handy for testing and validating parts of a circuit.

Despite duplicating much of the circuitry, we've managed to keep the end result compact. The basic version doesn't even have a display; it just has four knobs to dial in the voltage and current limit on each of the two channels.

It is certainly usable on its own, but there are evident benefits to being able to see the output voltages and currents as you work on your prototype. Later, we will present a neat little display module that not only provides readouts for the Breadboard PSU but also offers extra measuring channels to help you see what else is happening on your breadboard. A particularly handy facility

Features and Specifications

- **Two independent channels**
- **Each channel delivers 0-14V/0-1A (depending on input supply and load)**
- **Runs from 7-15V DC or USB 5V DC**
- **Plugs straight into breadboard power rails**
- **Four potentiometers provide all controls**
- **Optional metering add-on described on page 34 (shown above)**
- **Transient load regulation: <80mV DC + 350mV AC, 0-1A**
- **Transient settling time: 300µs, 0-1A**


CON1
D1 1N4004
A
K
DC_IN
REG1 78L05
IN
OUT
GND
10µF
+5V
JP2
REG
USB
10µF
5V_USB
DC_IN
+5V
JP1
JACK
BST
CON2
5V_USB
MOD1
VIN+
VOUT+
MT3608
DC BOOST
CONVERTER
MODULE
GND
DC_BOOST
DC
1N4004
MJE3055
B
C
E
LM78L05Z
COM
IN
OUT
BC547
VR1 10kΩ
V1POT
100kΩ
100nF
IC2: LMC6482AIN
IC2a
V1SET
V1CON
V1FB
I1SHUNT
VR3 10kΩ
I1SET
I1FB
IC2b
I1CON
100kΩ
Q2 BC547
I2FB
VR2 10kΩ
V2POT
VR4 10kΩ
51kΩ
IC3: LMC6482AIN
IC3a
I2SET
V2SET
V2CON
V2FB
V1CON
I1SHUNT
Q1 MJE3055
100mΩ
V1OUT
100Ω
Q3 MJE3055
I2SHUNT
V2OUT
IC3b
I2CON
Q4 BC547
10kΩ
GND
V1FB
V1POT
I1SET
I1FB
VINFB
CON5
V2FB
V2POT
I2SET
I2FB
CON6

Breadboard Power Supply – Main Board Circuit

Circuit operation

For the most part, the two channels of the Breadboard PSU have identical circuits that work independently. Having said that, they are supplemented by some common supply circuitry, as shown in Fig.1, the full circuit diagram.

You might notice that there are no regulator ICs in the main part of the circuit, at lower left. Instead, like the earlier Arduino PSU, the two outputs have their voltage regulated by op amps controlling NPN emitter-follower transistors (Q1 and Q3). The op amps use negative feedback to adjust the transistor base voltages to maintain the desired output voltages. This method of regulation can be a bit tricky due to the need for it to respond fast to changes in output load while at the same time, needing stability to avoid oscillation. Luckily, by using NPN emitter-followers, we avoid a large phase shift and gain a great deal of ‘local feedback’, so the op amps only need to make minor adjustments. More on that local feedback later.

As the supply is intended to be flexible, there are two different ways to power it. We’ll refer to the higher of these as 15V but its absolute maximum is 16V, the highest voltage that all circuit components can tolerate. Apart from this, its exact value is not critical and we expect users will stick to around 12-15V DC, as supplies delivering that range of voltages are pretty common.

Since the highest possible output voltage is around 2V below this rail, even a 9V battery is a valid option if you only need voltages up to about 5V. For example, if you are working primarily with microcontrollers.

A 5V rail also exists in the circuit for components that cannot handle 15V. JP1 and JP2 provide the means to configure the sources of the 15V and 5V rails, respectively, and are

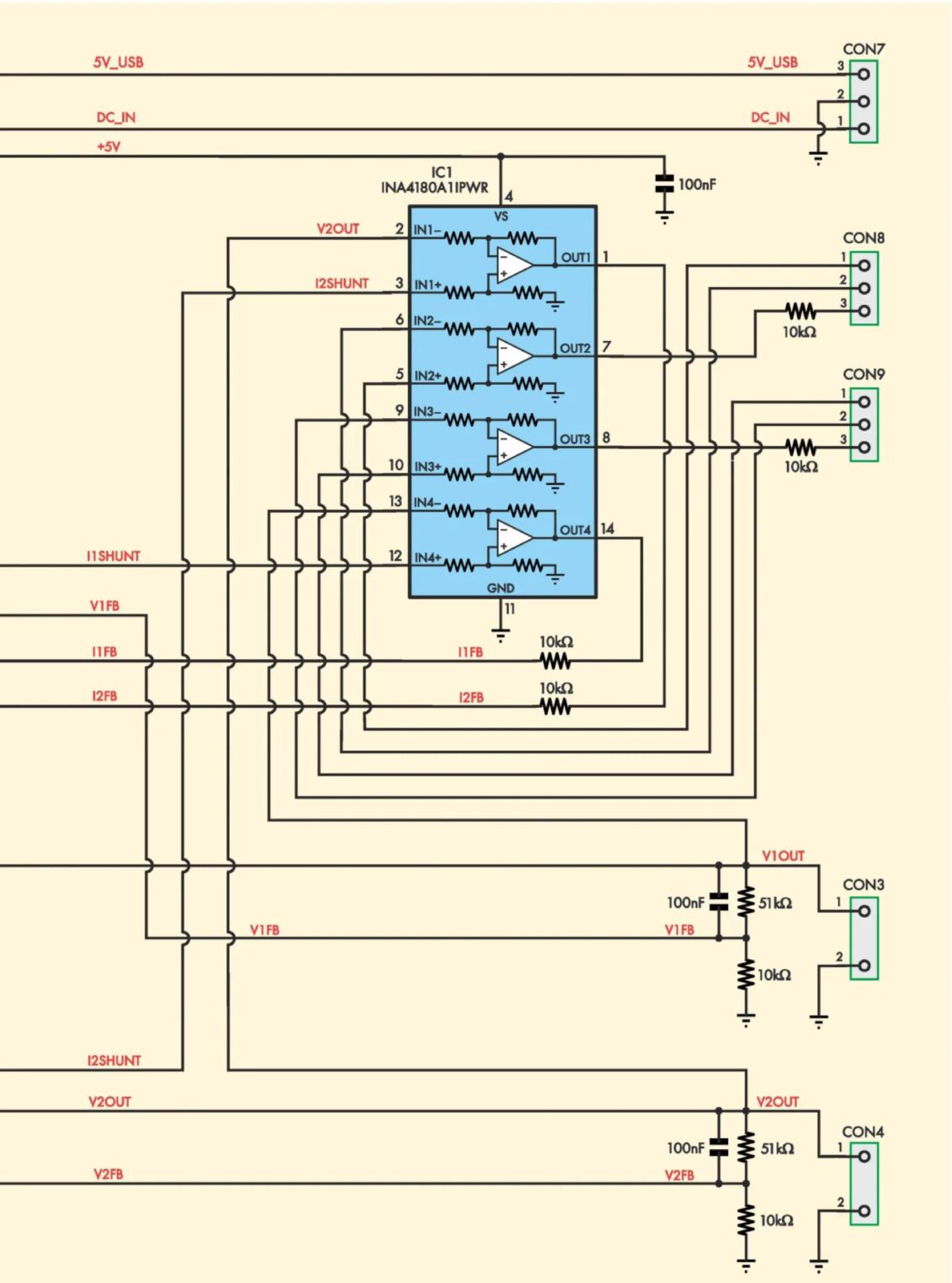


Fig.1: the Breadboard PSU shares some circuitry with the Arduino Programmable Power Supply but with no microcontroller in sight. Instead, four potentiometers provide control of two independent current-limited adjustable supplies.

Breadboard power modules like this are available from Jaycar and Altronics. They are inexpensive, convenient and can provide 5V and 3.3V rails as set by a switch, but they only supply one voltage at a time and don't have adjustable voltages or current limiting.

derived from DC input jack CON1 and USB socket CON2.

The incoming DC voltage at CON1 passes through reverse-polarity protection diode D1 to one side of JP1, allowing direct use of the incoming voltage for the 15V rail. The incoming DC at CON1 also feeds 78L05 linear regulator REG1, accompanied by an input bypass capacitor to produce a 5V rail, which goes to one side of JP2.

With JP1 and JP2 set to the 'REG' and 'JACK' positions, the power from CON1 supplies all the power rails on the Breadboard PSU.

When JP1 and JP2 are set to the alternative 'BST' and 'USB' positions, the 15V rail is derived from MOD1, an MT3608 boost module, which is supplied by 5V from the USB socket. The boost module has an adjustable output which must not be set any higher than 16V.

Other components common to the two supplies are a 51kΩ/10kΩ divider which provides a scaled version of the 15V DC rail to a pin on CON5 for external monitoring.

A four-channel INA4180A1 current shunt monitor (IC1) and its 100nF bypass capacitor are also shared between the two channels. It is powered from the 5V rail and used to monitor the output current of each channel plus optionally two other currents across pairs of points located on the breadboard.

Dual independent regulators

The remaining circuitry is independently allocated to one of the two channels and identical between the two. Therefore, we'll describe the function of one channel, with designations in brackets to indicate the equivalent part for the other channel.

10kΩ potentiometers VR1 (VR2) and VR3 (VR4) are wired across the 5V rail to set the voltage and current targets, respectively.

The control voltage from VR1 (VR2) passes through a 100kΩ resistor and is filtered by a 100nF capacitor to reject noise, while the current control voltage goes directly to its own 100nF capacitor. These feed pins 3 and 6 of dual rail-to-rail op amp IC2 (IC3), respectively.

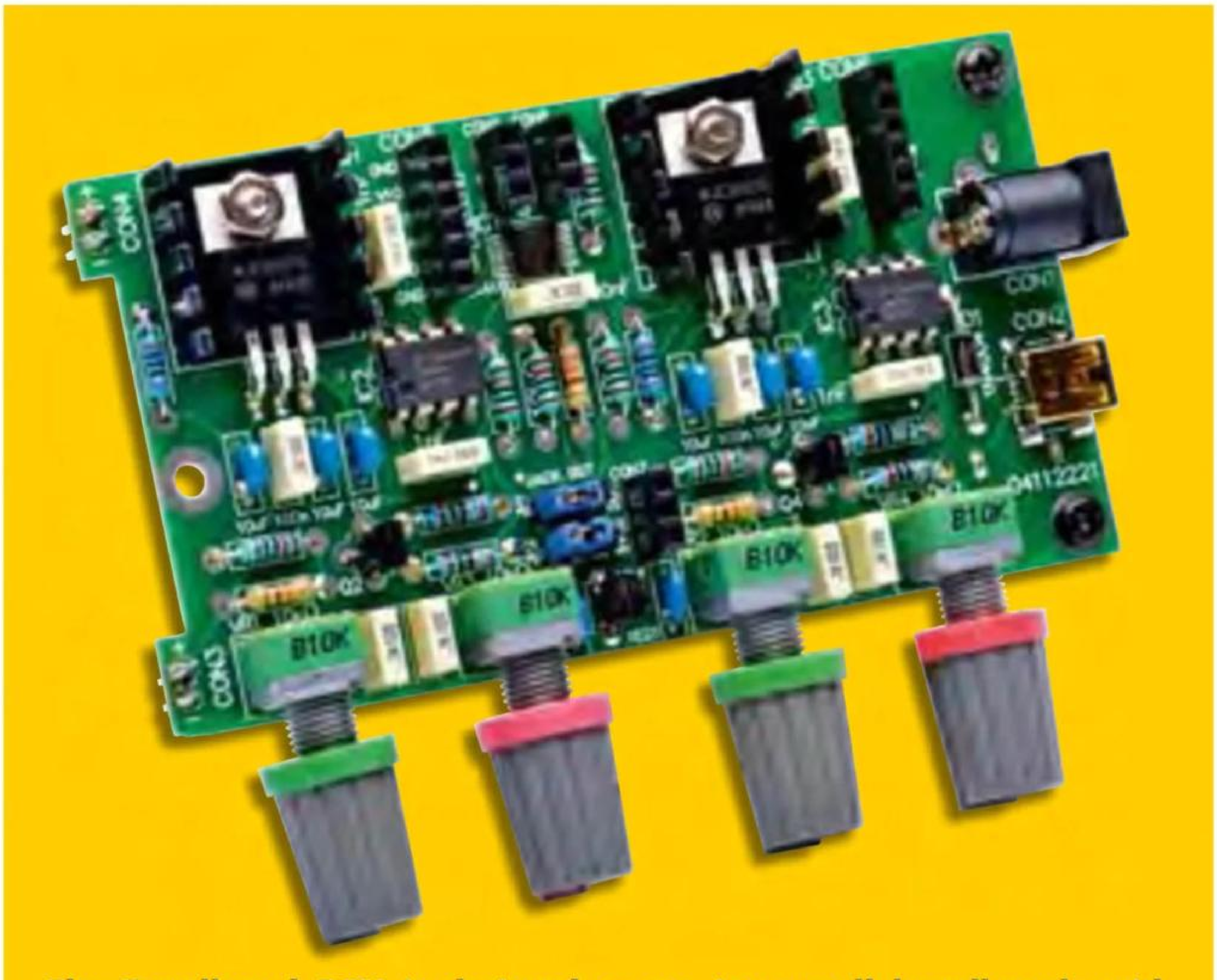
The 16V supply limit of the op amps dictates the maximum of 16V the design can handle.

IC2 (IC3) has a 10µF capacitor between its pin 4 and 8 supply pins, as its outputs can be expected to deliver a reasonable amount of current in sympathy with the PSU's load. Its supply comes from the 15V rail and circuit ground.

The voltage at pin 3 is compared with that at pin 2, which comes from a 51kΩ/10kΩ divider across output connector CON3 (CON4). This is fed from the emitter of MJE3055 NPN power transistor Q1 (Q3) via a 100mΩ current-sense resistor.

Q1's (Q3's) base is fed current from IC2's (IC3's) pin 1 output via a 100Ω resistor, filtered by a 10µF capacitor to ground. This low-pass filter works to prevent any oscillation that might occur. Q1's (Q3's) collector connects directly to the 15V rail.

With Q1's (Q3's) base voltage held steady by the 10µF capacitor, if the output voltage at its emitter drops, the base-emitter voltage inherently rises, causing it to conduct more current and 'prop up' the output. Similarly, if the output voltage rises, its base-emitter voltage drops, so it conducts



The Breadboard PSU is designed to tap into small breadboards with longitudinal power rails, such as the Jaycar Cat PB8820 seen earlier. One end rests on header pins in the breadboard, while the other stands on tapped plastic spacers.

less, moderating the output voltage. This local feedback provides fast corrections in response to load changes, keeping the output voltage reasonably steady in the short term. Slower corrections to its base drive from the op amp provide longer-term fine-tuning to improve regulation.

IC2a (IC3a) effectively tries to keep pins 2 and 3 at the same voltage by changing its output at pin 1. The voltage applied to CON3 (CON4) is thus a scaled version of the voltage on IC2a's (IC3a's) pin 3 with a low source impedance, forming the voltage control portion of the circuit.

For the most part, the output voltage is proportional (as per the 51kΩ/10kΩ divider) to the voltage set by the voltage at the wiper of VR1 (VR2), but it can vary, as we shall see shortly.

The 100nF capacitor across the 51kΩ feedback resistor helps the circuit respond quickly to changes by applying the full output voltage change to pin 2 of IC2a (IC3a) initially, rather than a scaled version. The 1nF capacitor between pins 1 and 2 of IC2a (IC3a) prevents oscillation by effectively increasing negative feedback at higher frequencies.

The 100mΩ shunt mentioned earlier connects to pins 12 and 13 (2 and 3) of IC1, the current shunt monitor. IC1 is an amplifier that produces a voltage at its pin 14 (pin 1) that is 20 times the difference between its input pins. This voltage passes to IC2b's (IC3b's) pin 5 non-inverting input via a 10kΩ resistor.

The shunt will induce a drop of 100mV at 1A which, when amplified by 20 by IC1, gives 2V/A at its output.

The current setting voltage from VR3 (VR4) is directly connected to pin 6 of IC2b (IC3b), the inverting input, and the output from pin 7 drives the base of NPN transistor Q2 (Q4) via a 100kΩ resistor.

Q2's emitter is grounded and its collector connects to IC2's (IC3's) pin 3, the voltage setting. An excessive output current causes IC2's (IC3's) pin 5 to rise above its pin 6 voltage, so output pin 7 goes high to turn on Q2 (Q4), pulling down the voltage reference until the current limit is no longer exceeded.

Another 1nF capacitor between IC2's (IC3's) pins 6 and 7 helps to reduce oscillation in the current control feedback loop, similar to the one in the voltage feedback loop.

Theoretically, the default circuit values correlate to a full-scale voltage setting of 30.5V on VR1 (VR2) and about 2.5A on VR3 (VR4), but we don't expect either of these will be achieved in practice. The dividers have mainly been selected so that the feedback and control voltages are below 3.3V, so an external monitoring circuit with a 0-3.3V input range can be used.

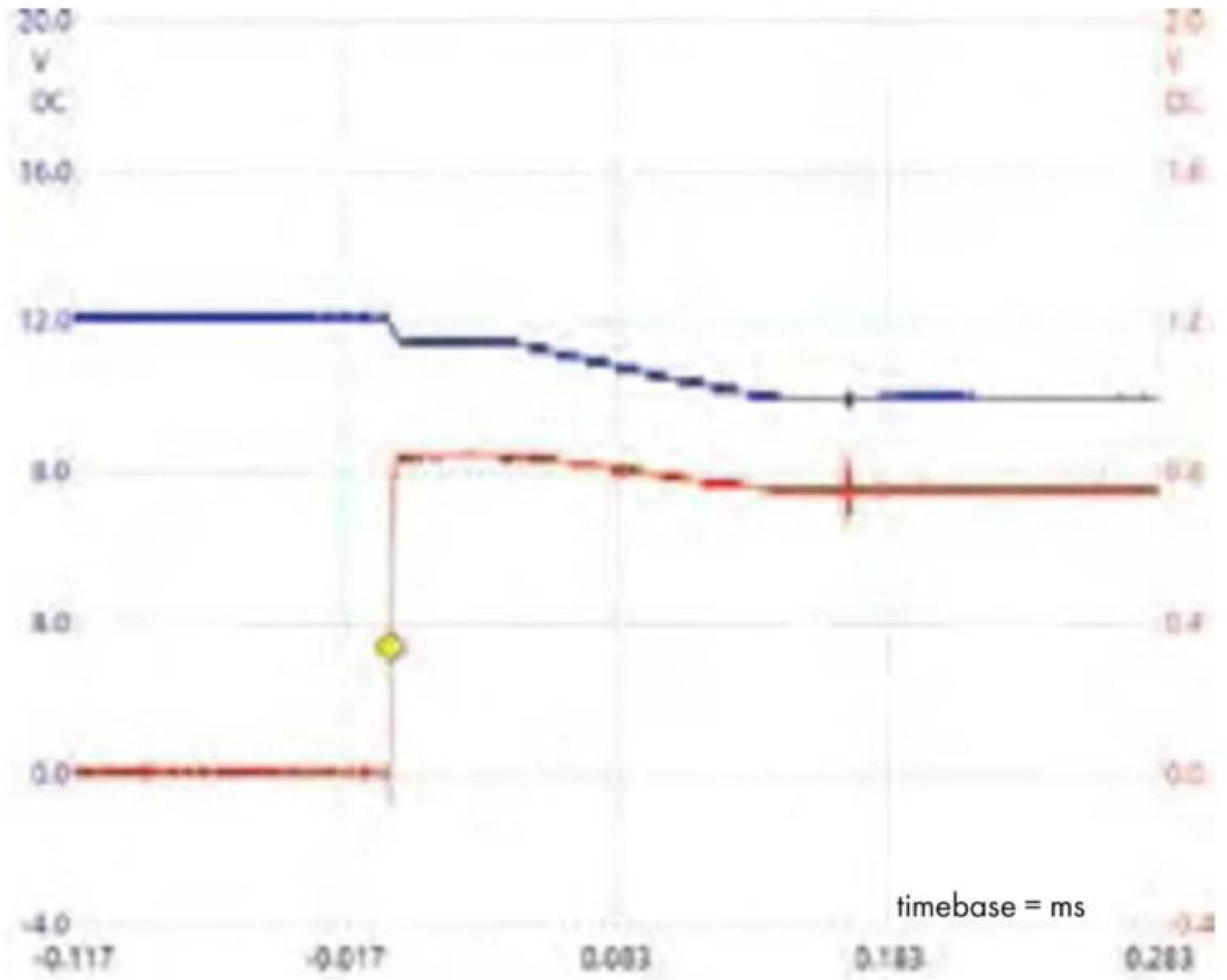
Parts List – Dual-Channel Breadboard PSU

1 double-sided PCB coded 04112221, 99mm x 54mm, available from the PE PCB Service
1 PCB-mounting 2.1mm inner diameter barrel socket (CON1)
1 SMD mini-USB socket (CON2)
2 2-way pin headers, 2.54mm pitch (CON3, CON4)
2 6-way female socket headers (CON5, CON6)
3 3-way female socket header (CON7-CON9)
2 3-way pin headers with jumper shunts (JP1, JP2)
2 12mm-long M3-tapped spacers
4 M3 × 8mm machine screws
2 M3 hex nuts
2 M3 shakeproof washers
2 small TO-220 finned heatsinks (no larger than 20 × 20 × 10mm)
1 MT3608 boost module (MOD1) **[SC4437]**
4 10kΩ 9mm linear potentiometer and knobs to suit (VR1-VR4) **[Jaycar RP8510 and HK773x]**
4 short component lead off-cuts or pieces of wire (for mounting MOD1)

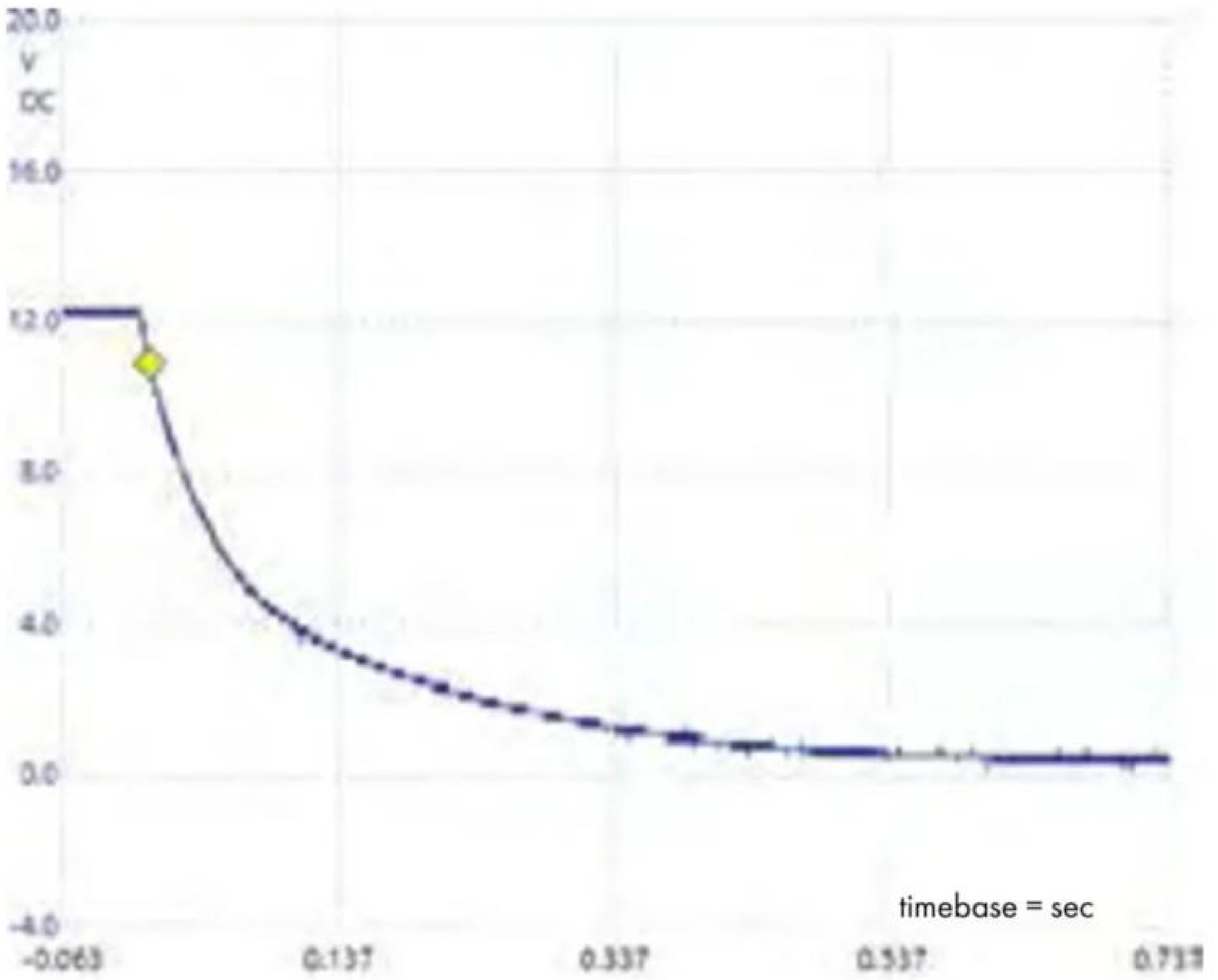
Semiconductors
1 INA4180A1IPWR quad current shunt monitor, TSSOP-14 (IC1)
2 LMC6482 dual rail-to-rail CMOS op amps, DIP-8 (IC2, IC3)
1 1N4004 400V 1A diode (D1)
2 MJE3055 60V 10A NPN transistors, TO-220 (Q1, Q3) **[Jaycar ZT2280]**
2 BC547 45V 100mA NPN transistors, TO-92 (Q2,Q4) **[Jaycar ZT2152]**
1 78L05 5V 100mA linear regulator, TO-92 (REG1) **[Jaycar ZV1539]**

Capacitors *(all SMD M3216/1206 X5R/X7R or MKT/ceramic radial)*
8 10µF 16V
7 100nF 50V
4 1nF 50V

Resistors *(all ¼W axial 1% metal film except as noted)*
4 100kΩ 3 51kΩ 7 10kΩ 2 100Ω
2 100mΩ M6432/2512 1W SMD



Scope 1: the response to a load change that triggers current limiting is about as fast as possible given the size of the output capacitor. The 23.5Ω load brings the output voltage down from 12V to 10V at around 400mA.



Scope 2: the slowest response under any situation is shown here, where the output voltage is instantaneously set to 0V with no load. The drop rate is limited by the output capacitor discharging through the output voltage divider.

If REG1 were replaced with a pin-compatible 3.3V type (that can withstand an input of at least 16V), the maximum voltage and current settings would be 20V and 1.65A. This would have the advantage of making the controls less sensitive, so accurate adjustments could be made more easily.

Supply options

Feeding in 12-15V DC to CON1 will give the best results, as the 5V output of REG1 will be better regulated than the 5V DC from a USB power supply. While the USB option is convenient, the boost module could impose a high current draw on the USB supply, which might cause unexpected glitches if it is overloaded.

If you only ever plan to feed in power via CON1, you could omit the USB socket and MOD1 and hard-wire the two jumpers.

The remaining connectors, CON5-CON9, are not needed when the Breadboard PSU is used in its standalone configuration, but can be used to connect to the display daughterboard, to be described on page 34.

If fitting these connectors, use header sockets. These not only match up with the headers on the display board, but they also make it easy to use standard breadboard jumper wires to connect these points to your breadboard circuit.

If you wish to tap into them for other purposes, CON5 and CON6 connect to most of the low-voltage signals mentioned earlier. CON7 provides breakouts for the incoming supplies from CON1 and CON2. CON8 and CON9 connect to the two spare current shunt monitor channels on IC1.

Performance

As the Breadboard PSU is based heavily on the circuit of the Arduino PSU, we knew it would work well. Still, we have produced a few scope grabs to give you an idea of what to expect.

The response to a current limiting event is critical to any bench supply's performance. Scope 1 shows the Breadboard PSU's output using our *Arduino Programmable Load* (June 2023) to apply a step load change from an open circuit to 23.5Ω, with an initial voltage of 12V.

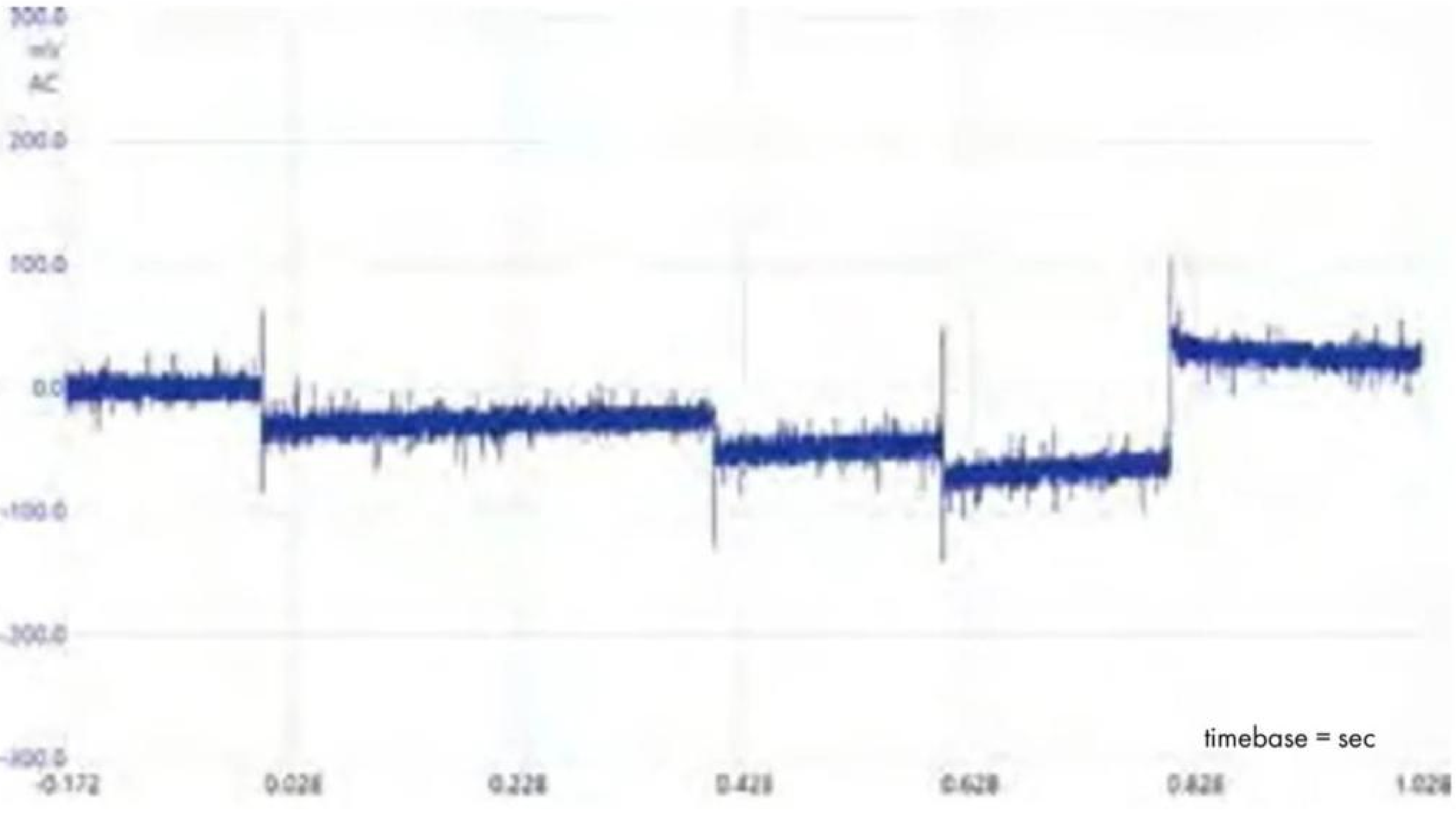
The blue trace is the voltage and the red trace is the current, peaking at around 500mA. As you can see, the Breadboard PSU starts reacting almost immediately and has settled to the new operating point after about 150μs.

Note that the time constant of the 10μF output capacitor into a 23.5Ω load is about the same duration, so most of the delay is actually due to the output capacitance discharging.

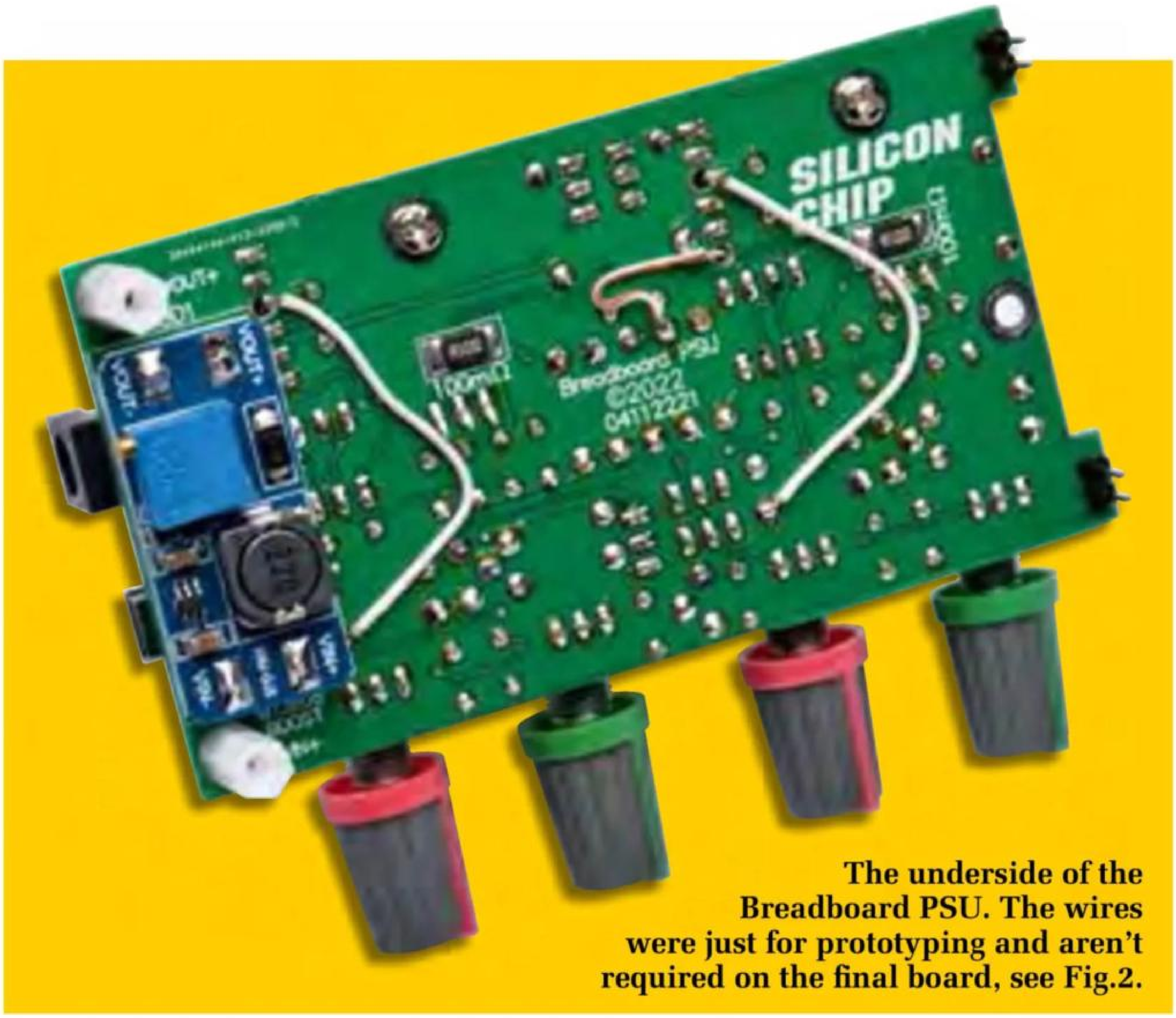
Scope 2 shows a step change in the voltage setting from 12V down to 0V (applied by shorting the wiper of VR1 to ground). Here, the output voltage takes half a second to decay due to the 10μF capacitor only being able to discharge through the 51kΩ/10kΩ divider.

Of course, any load impedance will cause this to happen much quicker. And it's doubtful that you'll be able to wind the potentiometer down any faster than that anyway.

Transient response is an important parameter for a regulator since it shows how much it will allow the voltage to vary if the load impedance changes fast. Scope 3 shows how the output voltage shifts with a series of load changes from 250mA to 500mA



Scope 3: this scope grab shows a series of load changes from 250mA to 500mA to 750mA to 1A and back to 250mA, with the worst deviation being under 100mV. We made these measurements directly at the output of the PSU. In practice, when using a breadboard, the variation is about three times greater due to the resistance of the breadboard conductors.



The underside of the Breadboard PSU. The wires were just for prototyping and aren't required on the final board, see Fig.2.

to 750mA to 1A and back to 250mA. As you can see, the change in output voltage is small, well under 100mA at 1A compared to no load.

Scope 4 shows a close-up of the transition from 250mA to 500mA in Scope 3. There are brief spikes of +300/–375mV, but it quickly settles to a steady voltage after about 300µs.

Construction

The Breadboard PSU is built on a double-sided PCB coded 04112221 that measures 99 x 54mm, as shown in Fig.2. It is available from the *PE PCB Service*.

Apart from the USB socket (CON2) and the current shunts, all the circuit parts can be through-hole types. It could have been smaller if we'd used more surface-mounting parts, but we would still need to leave room for the potentiometers and heatsinks for the transistors.

While this project is useful for beginners, constructors will need reasonable soldering skills as most shunt monitor ICs are only available as SMDs, and quad shunt monitor IC1 has fairly closely-spaced leads. Still, it is not that hard to solder with the right tools, a gentle touch and a bit of patience.

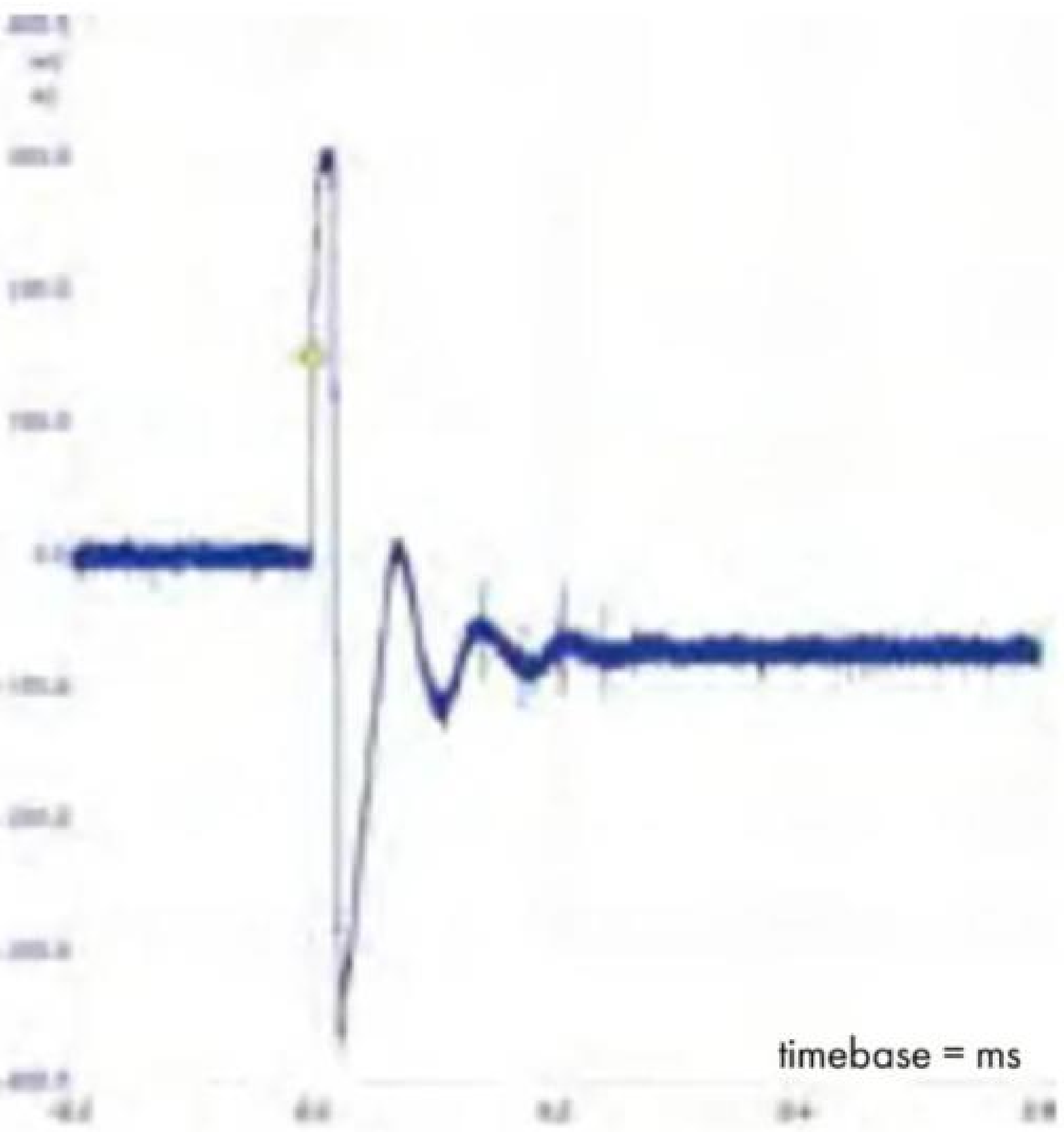
We've designed the PCB to accept either through-hole or surface mounting capacitors. So, if you have suitable SMD capacitors, you should fit them along with the other surface-mounting parts.

While Fig.2 shows SMD capacitors, our photos reveal we built the prototype with through-hole types. Note that SMD ceramics are usually cheaper than equivalent through-hole caps.

We've extended the pads for the smaller SMD parts to ease assembly. You might get away with simply using a fine-tipped iron, but flux and solder wicking braid will definitely help.

Start with IC1, which has the smallest leads of any of the SMDs. Apply flux to its PCB pads and align the part, checking that the pin 1 marking dots on the part and silkscreen line up. Tack one lead, then gently solder the remaining pins if all is still aligned (use a magnifier to check).

The solder fillets should form easily if you have the right amount of solder and flux. Use the braid to wick up any excess solder that might form bridges between the pins.



Scope 4: a close-up of the 250mA-500mA transition in Scope 3. There is a bit of overshoot, but it's close to being symmetrical.

CON2 is a surface-mounting USB socket that locks into place with tabs on its underside. Apply flux and carefully solder the two longer pads for power. After that, solder the larger mechanical tabs on the sides of the USB socket.

The two current shunt resistors are on the reverse of the PCB. Align them within their pads and tack one lead. Adjust the position so that the part is squarely within the silkscreen markings. Then solder the other lead and refresh the first lead if necessary.

Fit the capacitors now if you are using SMD parts. There are three different values and they are all spread around the PCB. Work with one value at a time to avoid mixing them up.

At this point, clean up any excess flux using an appropriate solvent. Be sure to let it dry thoroughly as many such solvents can be flammable.

A good strategy for the remaining PCB parts is to work from the lowest profile components up. Start with the resistors, as they are all mounted flat against the PCB. There are 16 of these around the PCB; check the silkscreen values against the resistors before soldering. A multimeter is the most reliable way to check the values as the colour markings can sometimes be ambiguous.

Fit the solitary diode D1 next. It is installed near the USB socket and should have its cathode band close to the USB socket.

If using through-hole capacitors, fit them next, checking the silkscreen marking against the part marking.

Then install the two op amps. Their pin 1 markings should align with the silkscreen and face to the left of the PCB. You could use sockets, although a socket for IC2 might foul the heatsink for Q1; check first before fitting it. It's generally acceptable to solder them directly to the PCB as you should not need to swap them unless they are faulty, which is unlikely.

There are three TO-92 parts; the two smaller transistors, Q2 and Q4, and voltage regulator REG1. Solder them in now, making sure to orient them correctly and don't get them mixed up.

Fit the various headers and jumpers next, but leave CON3 and CON4 to last as they are fitted under the PCB. Check Fig.2 and our photos to see what goes where.

Use three-way headers for the two three-way jumpers, JP1 and JP2. Slot them in place, solder one pin and check that the pins are perpendicular to the PCB surface before soldering the remaining pins. Leave the jumper shunts off until testing has been completed.

The remaining connectors on the top of the PCB (CON5-CON9) are all SIL socket types. It's even more critical to mount them perpendicular to the PCB as they are designed to plug into a second PCB mounted above.

The two larger transistors, Q1 and Q3, need heatsinks. Bend the leads back around 7mm from the body and thread the leads into the PCB holes. Slip the heatsinks in behind the transistors and secure both the transistor and heatsink to the PCB with an 8mm M3 screw on each.

A thin layer of thermal paste on the underside of the rabs of the transistor is optional, but will help with heat transfer. Add the washer and tighten the nut firmly to position the transistor and heatsink neatly and squarely. Then you can solder and trim the leads.

The remaining larger parts on the top of the PCB should be easy enough; just take care that they are neat. CON1 is adjacent to the CON2 USB socket and the four potentiometers are along one edge of the PCB.

You can fit the knobs now. For splined shafts, dial the potentiometers to their midpoints so that the slot is horizontal. Push on the knob so that the indicator points straight up, also at its midpoint. Then wind the knob anti-clockwise to its minimum position, so it is safe for testing.

We've used red knobs for the current limiting pots (VR3 and VR4) and green knobs (VR1 and VR2) for the voltage setting. Of course there are other colour combinations and you can choose whichever knob colour coding you prefer.

Next, fit the tapped spacers now as these form the legs at one end of the Breadboard PSU and will show you how much clearance you have to mount MOD1.

MOD1 is mounted to the underside of the PCB near CON1 and CON2. Since it covers the solder pads for some top-side components, ensure you haven't missed any parts. Trim any leads in that area short, so there is ample clearance.

Orient the module according to the VIN and VOUT markings on the PCB. Make sure you check the polarity too, as we have seen some variants of the MT3608 modules that have the connections reversed.

Then solder it in place using short lead off-cuts through the pads on both boards. Make sure it doesn't protrude further than the spacers; otherwise, it will carry the weight at this end of the PCB.

Also make sure that the underside of the module is not shorting against any leads, then trim the leads that are holding the module.

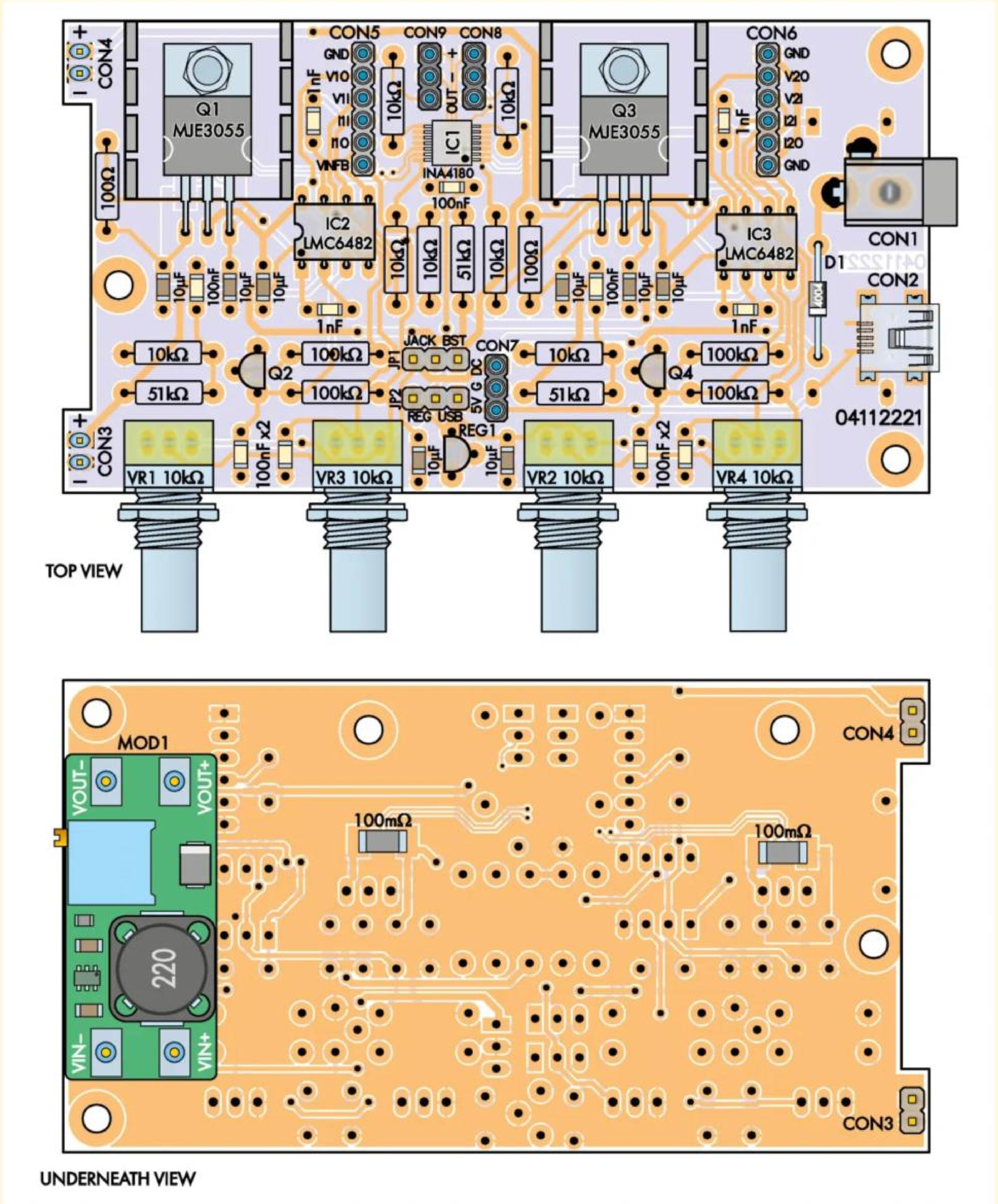


Fig.2: the Breadboard PSU is meant to be compact, so the PCB is pretty packed with components. CON3 and CON4 are fitted under the PCB to connect directly to a breadboard, while the two current-measuring resistors and boost module MOD1 are also on the underside. CON5-CON9 are mainly for fitting the display module. You can omit MOD1 and CON2 if you only plan to use the DC input at CON1.

Finally, fit CON3 and CON4. These can be aligned by pushing the header pins into the breadboard's power rail and then resting the Breadboard PSU PCB in place. We've aligned the positive pins with the red markings on the breadboard. Push everything down flat and then solder the ends of the header pins from above.

Testing

It's easy to run a few tests to verify everything is in order. You'll need a multimeter to measure a few different voltages for testing. All are referred to ground; the shell of CON2 (the mini USB socket) or pin 4 of IC2 or IC3 are good places to make this connection.

The following three paragraphs assume you have fitted MOD1. If you've left it off, skip them.

Leave JP1 and JP2 off and connect USB power to CON2. You should see 5V at the right-hand end (USB) of JP2 and the output from the boost module at the right-hand end (BST) of JP1.

Adjust the output from the boost module to be 15V or lower. If you know what your maximum working voltage will be, set this around 2V higher. A lower voltage will reduce dissipation in the transistors.

If you don't see the expected voltages, then perform some checks around CON2 and MOD1.

Disconnect USB power and apply a suitable supply to CON1. This can be anything from 7V to 15V; CON1 is configured for a positive tip as that arrangement is the most common.

The left-hand end of JP1 (JACK) will have a slightly lower voltage than the input at CON1 due to diode D1. If you see nothing there, then the diode or supply might have the wrong polarity.

You should measure about 5V on the left-hand end (REG) of JP2. If you don't, the problem is likely to be with REG1.

If all is well, connect your preferred power supply and set JP1 and JP2 to suit. In practice, that means both jumper shunts across the left and centre pins for power at the DC jack, or both jumper shunts across the right and centre pins for USB power.

Our photos show the jumpers set up for power being applied at the DC jack, although other combinations may be possible.

You should now be able to test the outputs with a multimeter. The leftmost potentiometers adjust CON3, which is next to them. The other potentiometers adjust CON4.

Move VR2 and VR4 (the current adjust potentiometers) slightly above their lowest position; otherwise, the output is completely shut off. Then slowly increase VR1 and VR3 and check that the voltage changes. The maximum voltage will be reached well before the clockwise position on the potentiometers and will be around 1V below the voltage selected by JP1.

Using it

Once it's plugged into a breadboard, there's not much more to using the Breadboard PSU. Use the potentiometers to adjust the voltages and current limits as needed.

With legs fitted at the end near CON1 and CON2, the Breadboard PSU rests on CON3 and CON4 on a breadboard at the other end. It's designed to be used more or less in the raw state.

If you don't plan to fit the display, you could use extra tapped spacers to mount a sheet of card or plastic above the exposed components for protection.

The transistors operate in linear mode, so they will dissipate quite a bit of power, depending on the settings and supply voltage. If the Breadboard PSU is current limiting into a short circuit, the dissipation will be at its highest.

The recommended heatsinks are suitable for up to a few watts, so with a 15V supply, you can set the current limit up to around 200mA without worrying about overheating the transistors. Even at higher dissipation levels, as long as you monitor the current and switch off the supply if it's drawing more than expected, it should survive brief overloads.

For higher supplied currents, especially if you only need much lower voltages, then you should consider a lower input voltage to reduce transistor dissipation.

As we mentioned earlier, we have also designed an add-on display module, as shown in the lead photo. It provides readouts of the set and actual currents and voltages. Its operation and construction are shown in detail starting on page 34 of this issue. We think it's a really handy addition – well worth making.

The display module can also estimate transistor dissipation by monitoring the voltages and currents, so it can help avoid situations that could overheat the transistors.

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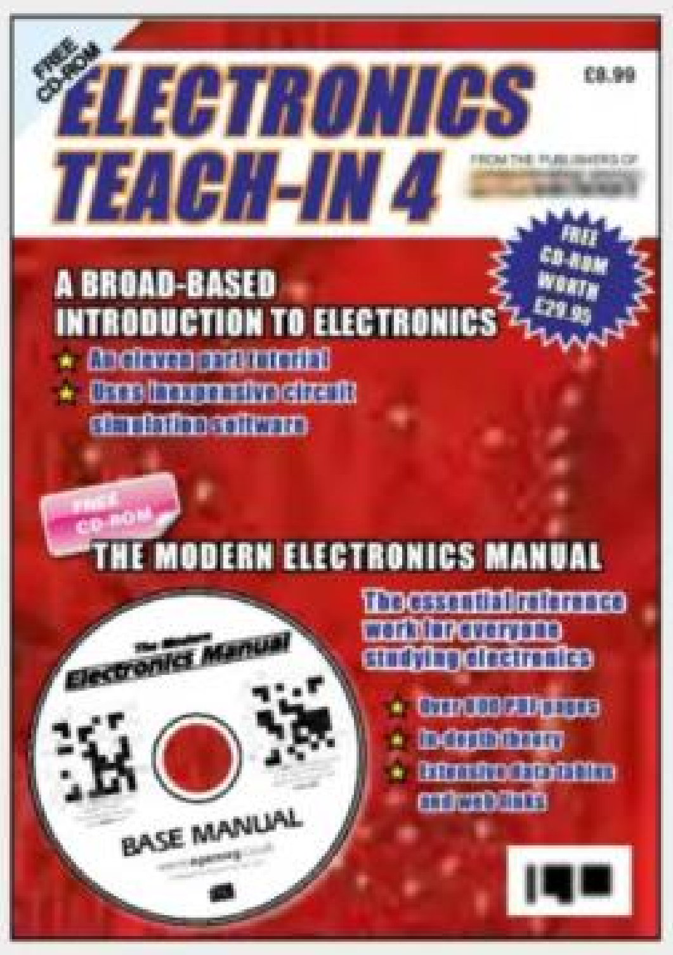

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- ■ Pi Projects
- ■ Pi Class
- ■ Python Quickstart
- ■ Pi World
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Tim Blythman's

Display Adaptor for the BREADBOARD PSU

The Dual Channel Breadboard PSU is a compact and handy add-on for prototyping. It slots straight into a breadboard's power rails and can run from a plugpack or USB supply. The Display Adaptor attaches to the Breadboard PSU and displays lots of handy data, such as the set and actual voltages and currents. It even has extra voltmeter and ammeter channels to help you analyse your prototype!

The Breadboard PSU is a compact unit that plugs into a breadboard, providing two voltage adjustable current-limited supply rails. It's a handy tool for prototyping and testing, but by itself, you won't know what voltages you've set or how much current is being drawn.

This add-on module solves that by providing readouts of the setpoint and actual voltage and current for each channel. Since it uses a microcontroller with many analogue inputs, we have added extra voltage and current monitoring channels that give you a lot of flexibility.

We've also included a pair of bicolour LEDs to provide useful status indications and a piezo buzzer to sound alerts. It even calculates an estimate of the dissipation that's occurring in the transistors in the Breadboard PSU, so you can avoid burning them out.

The PSU Display Adaptor simply mounts directly above the Breadboard PSU and doesn't take up any extra bench space.

Display Adaptor

When we designed the Breadboard PSU, we realised it would be pretty easy to add extra circuitry to monitor its operation. This is part of the reason for the numerous headers on the Breadboard PSU. Voltages are applied to pins on those headers that are proportional to voltages and currents in the circuit, making it easy for an add-on board to monitor the status.

Fig.3 shows the circuit of the Display Adaptor. It won't do much without the Breadboard PSU, so the components have been numbered to follow on from that circuit, except for CON5-CON9, which form the inter-board connections and are effectively common to both boards.

We'll also refer to parts on the Breadboard PSU, so you might need to refer to that circuit (Fig.1 on page 26).

Power for the Display Adaptor comes in via CON7, which has connections to ground, the 15V rail and the 5V rail from the PSU. It effectively combines the inputs from CON1 and CON2 on that board.

The Display Adaptor only needs a 5V rail to operate, so REG2 is a 7805 linear 5V regulator accompanied by 100µF input and output capacitors. This larger TO-220-type regulator has been mainly chosen to provide the higher current needed to drive the LED display backlight.

Jumper JP3 allows sourcing power from REG2 or the USB connection if preferred, but we recommend that this jumper be set to the REG position. That's because the regulator's output will be much more accurate and consistent than a USB supply.

IC4 is a 44-pin PIC16F18877 microcontroller, chosen for its numerous input/output (I/O) pins. It's effectively the same part used in the USB Cable Tester from November and December 2022), but in a compact TQFP package, which saves a lot of space.

IC4 has two 5V and two ground connections, each pair bypassed by a 100nF capacitor. The in-circuit serial programming (ICSP) pins are taken to CON13 for programming and debugging the microcontroller. If you have

Features and Specifications

- Uses a common 20x4 character backlit LCD
- Shows 11 statistics
- Four independent voltages and two currents displayed
- 100mV resolution on voltages, 10mA resolution on currents
- Typically 1% accurate, can be calibrated
- Includes indicator LEDs and over-current warning buzzer
- Shows dissipation estimate for PSU transistors
- Stacks on top of Breadboard PSU for minimal clutter

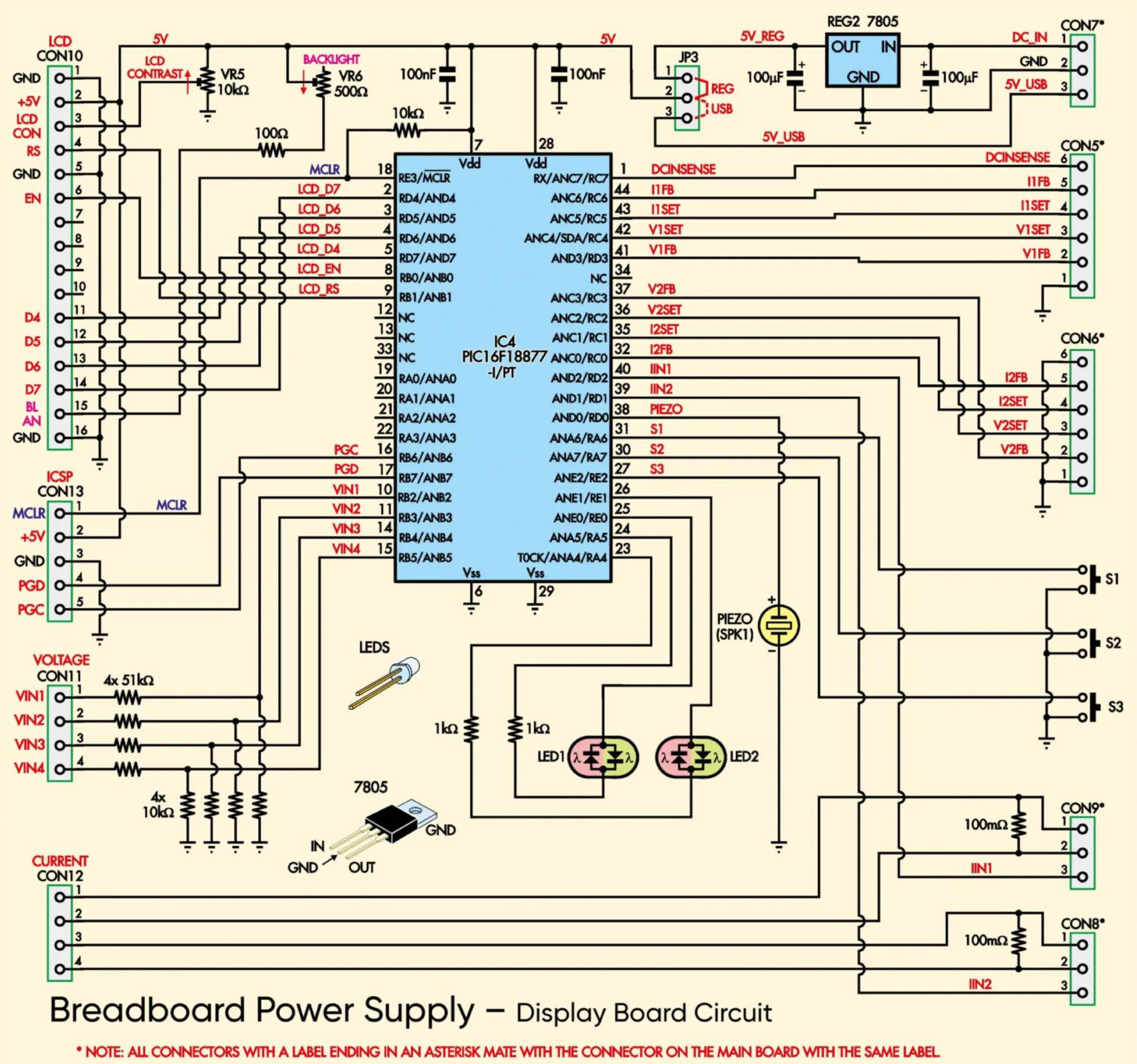

Breadboard Power Supply – Display Board Circuit
* NOTE: ALL CONNECTORS WITH A LABEL ENDING IN AN ASTERISK MATE WITH THE CONNECTOR ON THE MAIN BOARD WITH THE SAME LABEL.
LCD CON10
GND
+5V
LCD CON
RS
EN
D4
D5
D6
D7
BL AN
5V
LCD CONTRAST
VR5 10kΩ
BACKLIGHT
VR6 500Ω
100Ω
100nF
10kΩ
MCLR
LCD_D7
LCD_D6
LCD_D5
LCD_D4
LCD_EN
LCD_RS
IC4 PIC16F18877 -I/PT
Vdd
Vss
RE3/MCLR
RD4/AND4
RD5/AND5
RD6/AND6
RD7/AND7
RB0/ANB0
RB1/ANB1
NC
RA0/ANA0
RA1/ANA1
RA2/ANA2
RA3/ANA3
RB6/ANB6
RB7/ANB7
RB2/ANB2
RB3/ANB3
RB4/ANB4
RB5/ANB5
RX/ANC7/RC7
ANC6/RC6
ANC5/RC5
ANC4/SDA/RC4
AND3/RD3
ANC3/RC3
ANC2/RC2
ANC1/RC1
ANC0/RC0
AND2/RD2
AND1/RD1
AND0/RD0
ANA6/RA6
ANA7/RA7
ANE2/RE2
ANE1/RE1
ANE0/RE0
ANA5/RA5
T0CK/ANA4/RA4
5V_REG
REG2 7805
OUT IN GND
JP3
REG
USB
100µF
5V_USB
CON7*
DC_IN
DCINSENSE
I1FB
I1SET
V1SET
V1FB
CON5*
V2FB
V2SET
I2SET
I2FB
CON6*
IIN1
IIN2
PIEZO
S1
S2
S3
PGC
PGD
VIN1
VIN2
VIN3
VIN4
ICSP CON13
PIEZO (SPK1)
LEDS
1kΩ
LED1
LED2
VOLTAGE CON11
4x 51kΩ
4x 10kΩ
7805
IN GND OUT
CURRENT CON12
100mΩ
CON9*
CON8*

Fig.3: this circuit interfaces with that of the Breadboard PSU (Fig.1 on page 18) via CON5-CON9. CON7 provides power to the Display Adaptor, while CON5 and CON6 supply the voltages measured by the microcontroller IC4. CON8 and CON9 feed the two extra currents that can be measured between the two PCBs.

a pre-programmed microcontroller, CON13 does not need to be fitted. There is also a 10kΩ pullup resistor on IC4's $\overline{\text{MCLR}}$ pin to prevent spurious resets.

One of the great things about the PIC16F18877 is that its ports and pins are highly interchangeable. While it might look like a complicated chip with many pins, most PCB traces simply fan out in the required direction to the nearest connection point.

Practically all I/O pins are internally connected to the microcontroller's ADC (analogue-to-digital converter) peripheral, so we can use them to read and monitor external voltages.

Nine such voltages come from the Breadboard PSU through CON5 and CON6. Eight of these correspond to the actual and setpoint (target) voltages for the current and voltage of each of the two PSU channels.

The remaining voltage to monitor is a divided version of the so-called 15V rail, allowing it to be measured too. This is handy to know as it is the DC supply for the PSU outputs and will dictate such things as the maximum output voltage. You might find this handy to monitor if you're running the Breadboard PSU from a battery and want to check that it's not going flat.

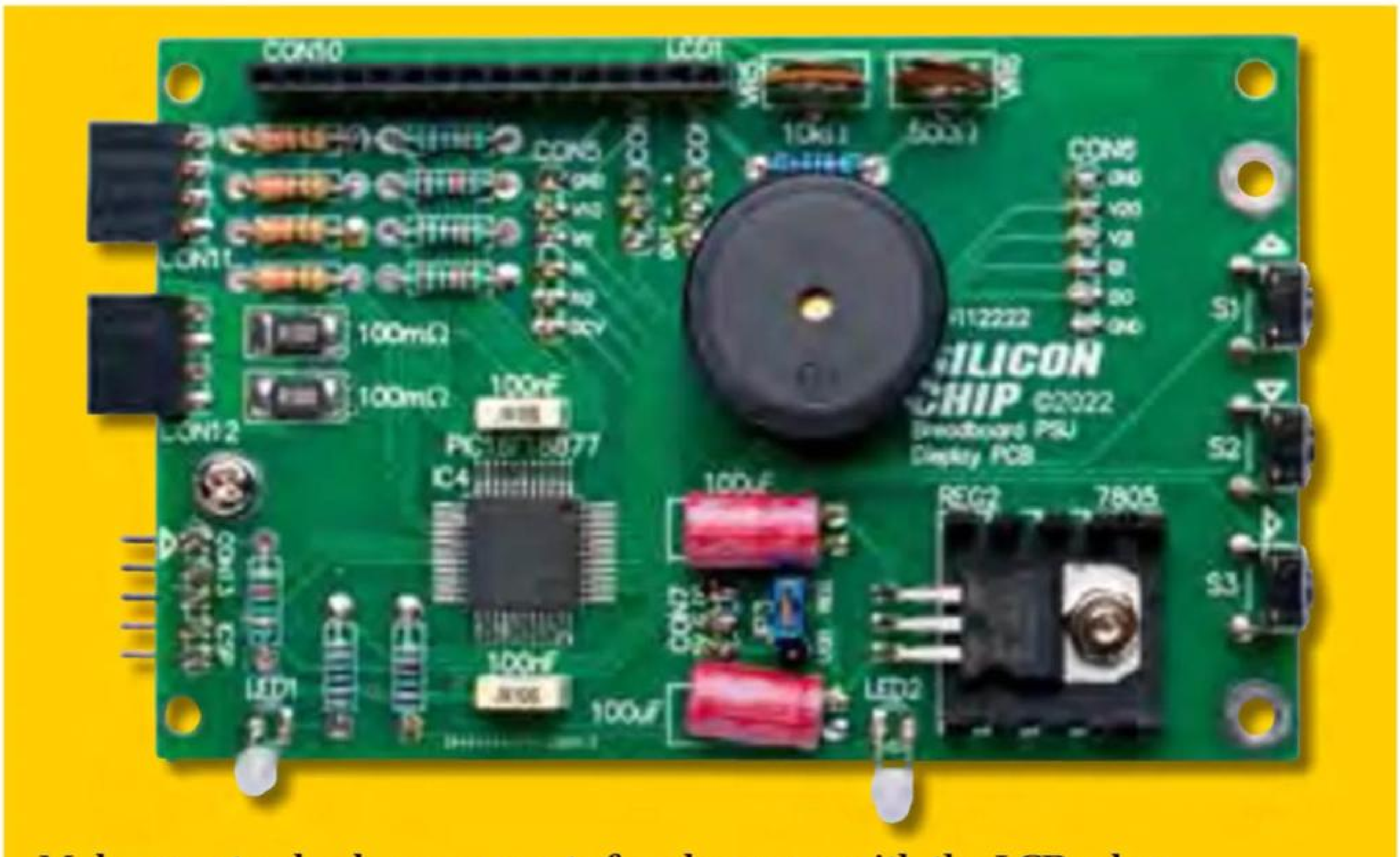
Note that this reading is also used in the calculations to determine the dissipation in the Breadboard PSU's power transistors.

Using a battery is an easy way to get a floating (ie, not connected to earth) power supply and is something that the Arduino Programmable PSU could not do without being connected to a laptop computer running on its own battery.

Handy additional inputs

Four more analogue voltages are monitored that are derived from the four 51kΩ/10kΩ voltage dividers connected to four-way header CON11. These are the same ratios used on the Breadboard PSU, giving the same nominal 30.5V scale against a 5V reference. You can use these independent voltage channels to monitor your breadboard prototype.

Using the same divider ratios mean that a single (nominal) calibration factor can be used for all voltage inputs. The input impedance at these pins is much lower than a multimeter, but we think they'll still be convenient when you need to check multiple voltages in your circuit simultaneously.



Make sure to check components for clearance with the LCD when assembling the Display Adaptor PCB.

CON12 is another four-way header that provides the facility to monitor two currents in your circuit. Each requires two connections as the current needs to pass in, go through the current sense resistor and back out to the circuit under test.

The arrangement is the same used for monitoring the output currents of the Breadboard PSU. A voltage appears across the 100mΩ shunt resistor in each channel when current passes through them. That voltage is amplified by IC1 on the Breadboard PSU PCB and returns to the Display Adaptor via the third pins of CON8 and CON9, to be read by a further two ADC inputs.

We can do this because IC1 is a quad-channel device and only two of its channels are used by the Breadboard PSU hardware.

The voltages on the current monitor inputs must be no higher than the INA4180's 26V limit. That seems unlikely, given that the circuit on the breadboard is presumably powered by the maximum 15V outputs of the Breadboard PSU.

The 20-column, four-row alphanumeric LCD module connects to the circuit via header socket CON10. 10kΩ trimpot VR5 wired as a voltage divider provides a contrast control voltage into pin 3 of the LCD.

500Ω trimpot VR6 is wired as a variable resistor to allow the LED backlight brightness to be adjusted. This can save power by dimming the backlight when running from a battery.

Six control signals go between CON10 and IC4 to control the LCD module in four-bit mode. IC4's digital outputs drive these pins to clock data and commands into the LCD.

CON10 also provides power for the LCD controller and backlight LED, the contrast voltage generated by VR5 and provides a connection to pull the RD/$\overline{\text{WR}}$ pin low. The micro doesn't read from the display controller, saving an I/O pin.

Another four digital output pins of the micro drive bi-colour LEDs (LED1 and LED2) via 1kΩ dropping resistors. Each LED uses two I/O pins and, depending on which is high and which is low, either the red or green LED element (or neither) is lit.

Finally, another digital output is used to drive piezo sounder SPK1.

Firmware

Microcontroller IC4's main task is to read the raw analogue voltages on various pins, scale them according to a calibration factor, and display them on the LCD. Screen 1 shows the resulting display.

The first line shows the parameters set by the potentiometers on the Breadboard PSU, indicated by an 'S'. These are the CON3 voltage (as set by VR1), CON3 current (VR3), CON4 voltage (VR2) and CON4 current (VR4) targets.

As the current-limiting circuitry on the Breadboard PSU pulls down the reference voltages using Q2 and Q4, the displayed voltage can dip slightly (up to around 0.2V) during current limiting.

The value of the 100kΩ resistors connected to the wipers of VR1 and VR2 is a compromise between this side-effect and providing a low impedance path for the control voltage. So take care not to set these voltages while current limiting is active.

Note that the 'A' (for amps) at the end of the first line is implied due to the space needed for the 'S' at the start. We've also used custom narrow characters for the units to provide visual separation. These characters use the display's character generator RAM feature.

The second line shows the corresponding measured values, marked by the leading 'A' for 'actual'. For the most part, the voltages should match the setpoints except when the current limit is active, in which case the current should match its setpoint.

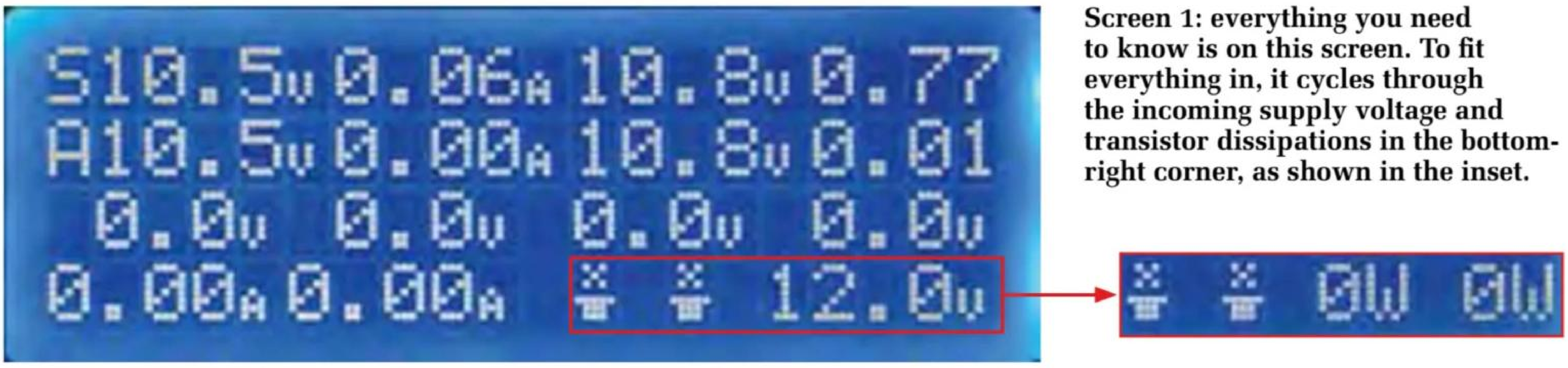
The third line shows the 'bonus' voltage readings from CON11, while the first two readings on the fourth line are the currents measured at CON12.

The small icons that follow indicate whether audible alarms are active for the CON3 and CON4 outputs, respectively.

The remaining three statistics share the last five character slots in the lower-right corner of the screen. The dissipation in each main regulator transistor is calculated as the CON3 or CON4 output voltage subtracted from 15V rail voltage, multiplied by the appropriate current.

The display cycles every two seconds between showing the 15V rail voltage (which won't necessarily be 15V) and the two calculated dissipation figures of Q1 and Q3 on the Breadboard PSU.

This is possible because the dissipation is expected to be in the range of single digit (0-9) watts, so it can be displayed very compactly. You can see this in the Screen 1 inset. If the reading is above 9W, it is clamped to 9W for simplicity.



Screen 1: everything you need to know is on this screen. To fit everything in, it cycles through the incoming supply voltage and transistor dissipations in the bottom-right corner, as shown in the inset.

Besides driving the display, which takes up most of the microcontroller's time, it also monitors pushbutton switches S1-S3 and lights up LED1 and LED2 depending on the prevailing conditions.

The purpose of those switches and LEDs will be described later, in the section on using this unit. In brief, the buttons allow the audible alarm for either channel to be toggled and all the values displayed to be calibrated. The LEDs indicate when either channel is in current limiting or otherwise unable to achieve the desired voltage.

Construction

Start by fitting out the PCB for the Display Adaptor, which measures 99 × 63mm and is coded 04112222, referring to overlay diagram Fig.4. THe PCB is avaliiable from the *PE PCB Service*.

There are five surface-mounting parts, but none are that difficult to handle. You should have flux and solder wicking braid at the very least, as the pins on IC4 are fairly close together. Flux will help the solder flow in the right places, and the braid will help remove it if it gets where it shouldn't.

We also recommend having tweezers, a fine-tipped soldering iron, good illumination and a magnifier to help you check your soldering.

Start by soldering the microcontroller, IC4. Lay down some flux on the pads and align it on all four sides. The TQFP part is a bit more fiddly than, say, an SOIC part that only has pins along two sides.

Roughly place it and check that the pin 1 dot matches the PCB silkscreen. Tack one pin in place and check that it is flat and that all the pins are above the correct pads. If not, apply heat to the soldered pins and gently adjust the chip's position with tweezers until all the pins are perfectly aligned.

With parts like this which have closely-spaced pins, try to keep the iron away from the top of the pins and work on where the pin touches the PCB pad. That helps to avoid solder bridges forming between the pins.

With it aligned, go around and solder each pin, starting on the opposite side from the pins you initially tacked. Finish by retouching the first pin(s) if necessary. Then use solder wick to remove any bridges that have formed. Some more flux and a touch from the soldering iron can help tidy up any joints that don't look right.

Follow with the two 100nF capacitors near IC4, which are not polarised.

The shunt resistors are the other surface-mounting parts; they will be much easier due to their larger size. Use a similar technique of soldering one lead, checking for alignment and then solder the other side.

With all the SMDs fitted, clean off any flux residue using a flux remover or alcohol (eg, isopropyl or methylated spirits) and a lint-free cloth and/or nylon brush. Allow it to dry fully before proceeding.

You can then fit the through-hole resistors. There are four different values, so check each part with a multimeter against the silkscreen printing to confirm that the correct value is placed in the correct location. Most of them have values that are powers of ten, so their markings will be similar, but they will easily be distinguished by a multimeter.

The two 100µF capacitors near REG2 are polarised (the longer leads go to the pads marked +) and must be mounted on their sides to leave enough clearance for the LCD to fit above. It's easiest to bend their leads before soldering. Check which way this will be (based on the polarity), slot them into place and confirm that the positive marking aligns with the longer lead before soldering.

Although the Breadboard PSU won't be subjected to much movement, there is no harm in securing the capacitor bodies to the PCB with a dab of neutral-cure silicone sealant.

REG2 is fitted similarly to the transistors on the Breadboard PSU PCB. Bend the leads back 90° around 7mm from the body of the regulator, slot them into the holes in the PCB and then slip the heatsink underneath. Thread the machine screw through from below and loosely secure it with the washer and nut.

Adjust the regulator and heatsink to be square and within the silkscreen markings, then tighten up the nut, being careful not to twist the regulator. The leads can then be soldered and trimmed.

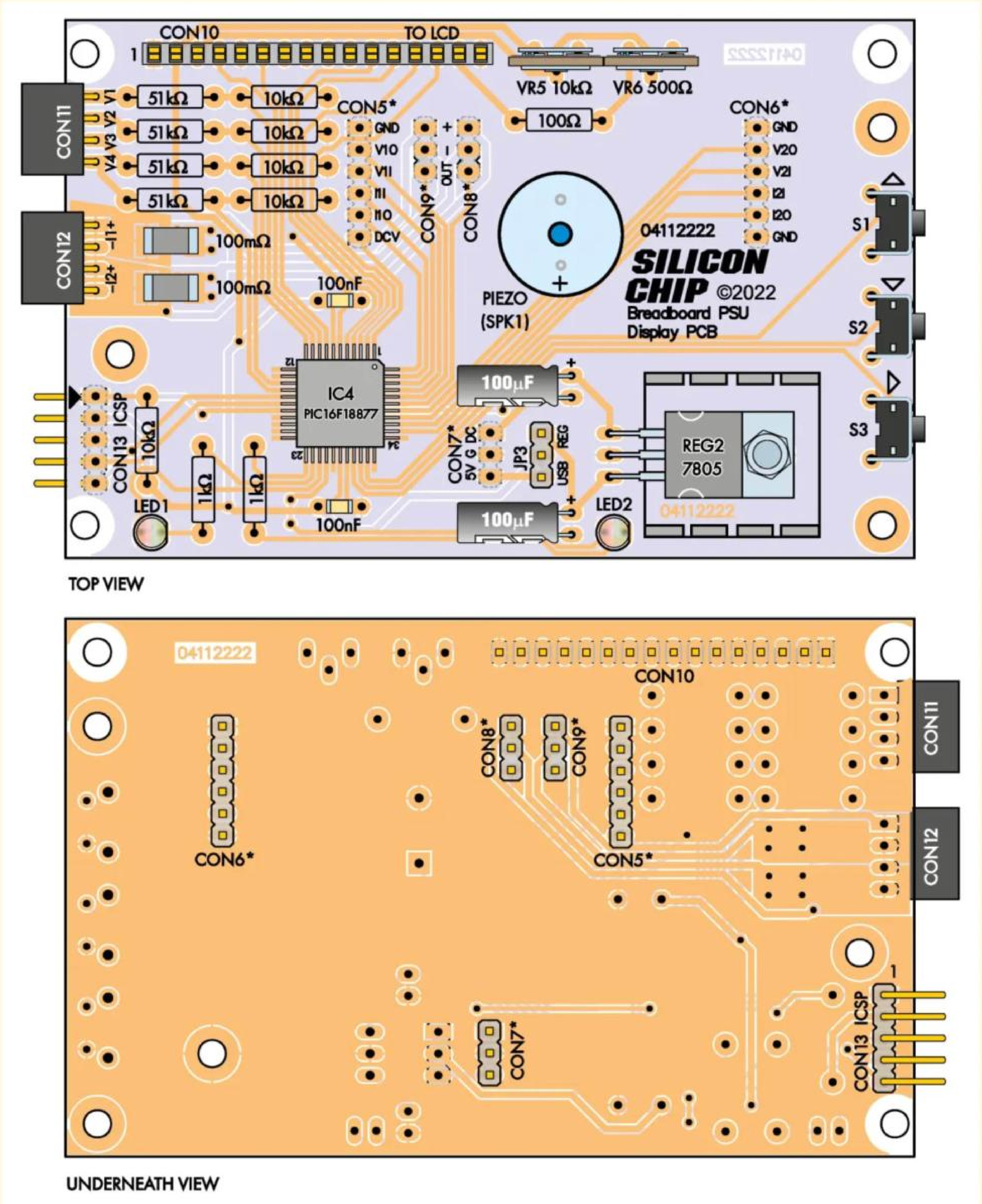
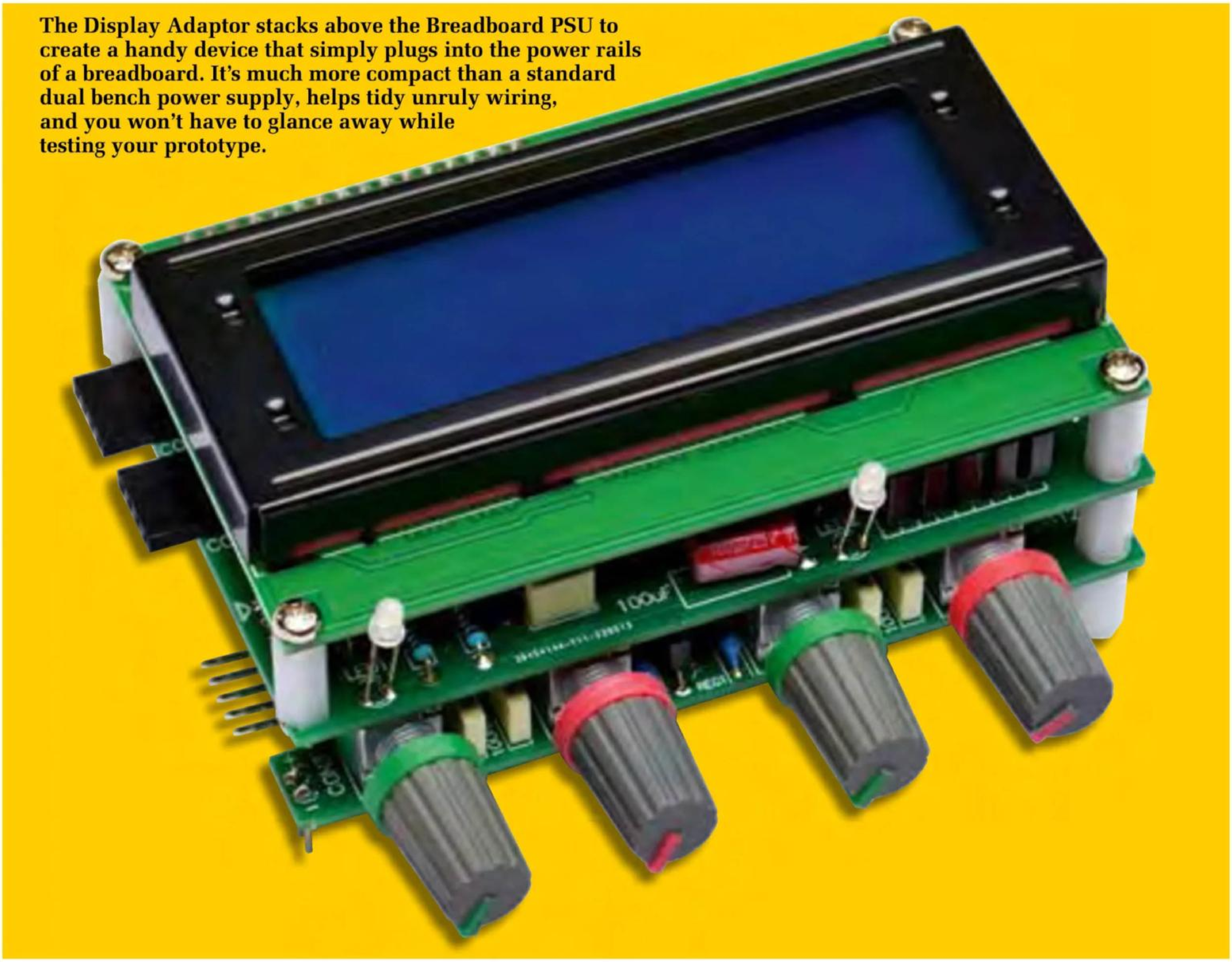


Fig.4: the Display Adaptor is much the same size as the LCD module that sits above it. Pin headers CON5-CON9 are fitted below this PCB to connect to the Breadboard PSU. We also recommend that the ICSP header (if fitted) go underneath the PCB to give clearance for the LCD. The LEDs are installed last to align with the top of the LCD, while the trimpots and piezo should be checked for clearance below the LCD.



The Display Adaptor stacks above the Breadboard PSU to create a handy device that simply plugs into the power rails of a breadboard. It's much more compact than a standard dual bench power supply, helps tidy unruly wiring, and you won't have to glance away while testing your prototype.

Solder the three-way header for JP3 now, then fit the jumper to the REG position (across the top two pins), unless you have configured the Breadboard PSU to use USB power.

Right-angle switches S1-S3 will only fit one way, with their buttons facing out from the PCB. Just check that they are lined up neatly before soldering.

CON11, CON12 and CON13 (if needed) can be soldered next. We used right-angle female headers for CON11 and CON12 as these will accept jumper wires for prototyping. If you can't get right-angle types then you can carefully bend the pins of vertical types before soldering.

We installed CON13 underneath the Display Adaptor PCB as this gave the best clearance to the adjacent spacer for connecting a programmer. Check our photos for how CON11, CON12 and CON13 look on our prototype.

Final assembly

Remove the screws and tapped spacers from the Breadboard PSU, then fit the tapped spacers to the LCD module, so that we can use it to align and check the next steps of the assembly.

Orient the LCD module so that the 16-way header is at upper left with the display upward. If there are text labels for the pins, these should be the right way up. This is the normal orientation of the LCD module as we describe the assembly in the following.

The tapped spacers along the left (top and bottom) and top right of the LCD module should be secured with the short (5-6mm) machine screws. The spacer at lower right uses the 32-35mm machine screw as this forms the top of a stack of three spacers.

Mount the trimpots similarly to the switches. They will need to be pushed down firmly against the PCB to ensure they do not foul the LCD module above. You can check this by temporarily slotting the LCD module above, using the longer machine screw for alignment.

Then fit the piezo buzzer, making sure to check the polarity markings. Some of these devices are pretty tall; check the clearance there too.

If you haven't yet fitted the 16-way header to the LCD module, do this now. You can then use it to square up the 16-way female header attached to the Display Adaptor PCB that connects to the LCD module. Solder the female header to the Display Adaptor PCB – and then separate the two boards.

Temporarily fit three tapped spacers above the Breadboard PSU PCB, with short screws coming up from below. This will allow you to align the headers from Display Adaptor PCB.

If you haven't fitted CON5-CON9 to the Breadboard PSU PCB, do that first. Then slot the corresponding headers into the top of them, rest the Display Adaptor PCB over them, and solder them while everything is aligned.

Separate the two PCBs and remove the temporary spacers from the Breadboard PSU PCB.

The final components to be soldered to the Display Adaptor PCB are the two LEDs; they are positioned to poke over the top of the LCD module's PCB, making them just visible below the display. We will fit them after the LCD module is fitted to the Display Adaptor PCB.

The Display Adaptor PCB should have six unoccupied M3 mounting holes at this stage. The four in the corners are for the LCD above, so leave them free.

Fit the other two 'spare' mounting holes with tapped spacers. Put a tapped spacer below the one on the left (between CON12 and CON13) and secure it with a short machine screw from above. The hole at upper right (next to S1) should be fitted with the 20-25mm machine screw and secured with a tapped spacer below.

Fit the LCD module to the Display Adaptor and secure it with three short machine screws into the tapped spacers with short screws at their other ends. The bottom right corner can have another tapped spacer threaded over the 32-35mm screw that is already fitted.

Now orient the LEDs so that they light up red when the left-most lead is more positive than the right. You can use a multimeter on diode test mode to check that, then solder the LEDs so they protrude just above the LCD module.

Now add the Breadboard PSU PCB to the bottom of the stack. Check for clearances and trim any leads that might foul components below. If things are still very close, you can add some insulating material between the two.

Secure the Breadboard PSU PCB at its left-hand (breadboard) end by a machine screw into the underside of the tapped spacer. The last two tapped spacers cover the two exposed screw threads on the right to form the feet, in a similar manner to the bare Breadboard PSU. This secures the other end of the PCB stack and completes the assembly.

Powering it up

If you wish to tread cautiously when applying power for the first time, use a current-limited PSU set to around 100mA or a 9V battery. Make sure there isn't anything connected to CON3 or CON4.

The LCD backlight should light up, but you might need to adjust the contrast trimpot VR5 to get a legible display. After that, it should look much like Screen 1, although the displayed values will probably differ.

Check that the voltage at bottom right is about half a volt below the supply at CON1. With nothing connected, it should cycle between the input voltage and '0W 0W'.

Pressing S1 or S2 should toggle the alert icons at lower right. If one of the LEDs is red, the piezo should sound when its alarm is unmuted. If this isn't the case, the LEDs may be reversed.

To check this, dial up the current limit to about halfway; you should get a reading of about 1.25A on the top line. Set the voltages to their minimums. This results in a state where the LEDs should definitely be green.

The easiest way to force a red LED alarm state is to dial the voltage potentiometers to their maximum and the current limits to their minimum. This should also result in an audible alarm from the piezo if the alarm is unmuted.

Finally, you can check that S3 cycles through the various calibration screens. If that's the case, then the Display Adaptor is working as expected. If the LEDs show the wrong colour, desolder them and swap their leads.

Calibration

In regular use, a single screen displays all applicable information, previously shown in Screen 1. This is shown at power-up, so you can use the Display Adaptor without pressing any buttons.

If the readouts you see on the Display Adaptor are off by more than 5%, we recommend checking your construction, as it should be closer than that without calibration. Start by checking all the divider resistors.

The 1% tolerance components specified will be more than adequate for most purposes and within the resolution of the displayed values, so calibration is optional.

Pressing tactile pushbutton S3 accesses the calibration factors for all the displayed parameters, except the transistor dissipations, which are set by their constituent voltages and currents. Each press of S3 simply cycles through each in turn until you return to Screen 1.

Screen 2 shows a typical calibration page. The calibration factors are displayed in the same order as on the main screen, but the second line of text also describes the parameter.

The third line shows the calculated value of that parameter using the current calibration factor, which is seen on the line below. The calibration factor is changed using S1 and S2 to adjust up and down.

Thus, the simplest way to calibrate is to use a multimeter to measure the parameter (voltage or current) and then adjust the calibration factor until they agree.

Because all voltages use the same 51kΩ/10kΩ divider, their default calibration factors are the same. Similarly, all currents have a different corresponding calibration factor.

Use a multimeter to read the voltage or current you wish to calibrate. Note that for currents, you will need to apply some sort of load and make

Parts List – Breadboard PSU Display Adaptor

1 double-sided PCB coded 04112222, measuring 99mm x 63mm
1 20×4 alphanumeric LCD with backlight (LCD1)
1 self-oscillating piezo transducer (SPK1)
1 10kΩ side-adjust trimpot (VR5) **[Jaycar RT4016]**
1 500Ω side-adjust trimpot (VR6) **[Jaycar RT4008]**
3 right-angle SPST tactile pushbutton (S1-S3)
2 6-way pin headers (CON5, CON6)
4 3-way pin headers (CON7-CON9, JP3)
1 jumper shunt (JP3)
1 16-way female header (CON10; for LCD1)
1 16-way header (for LCD1)
2 4-way right-angle female headers (CON11, CON12)
1 5-way right-angle pin header (CON13; **optional**, for ICSP)
1 small TO-220 finned flag heatsink
7 12mm-long M3 tapped spacers
1 M3 × 32-35mm panhead machine screw **[Jaycar HP0418]**
1 M3 × 20-25mm panhead machine screw **[Jaycar HP0414]**
7 M3 × 5-6mm panhead machine screws
1 M3 shakeproof washer
1 M3 hex nut

Semiconductors
1 PIC16F18877-I/PT 8-bit microcontroller programmed with 0411222B.HEX, TQFP-44 (IC4)
1 7805 5V 1A linear regulator, TO-220 (REG2)
2 bi-colour red/green 3mm LEDs (LED1, LED2) **[Jaycar ZD0248]**

Capacitors
2 100µF 25V radial electrolytic
2 100nF 25V M3216/1206 X5R/X7R ceramic, radial ceramic or MKT

Resistors *(all ¼W 1% axial except as noted)*
4 51kΩ 5 10kΩ 2 1kΩ 1 100Ω
2 100mΩ M6432/2512 1W SMD

PoLabs

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PoScope Mega1+
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- resolution up to 12bit
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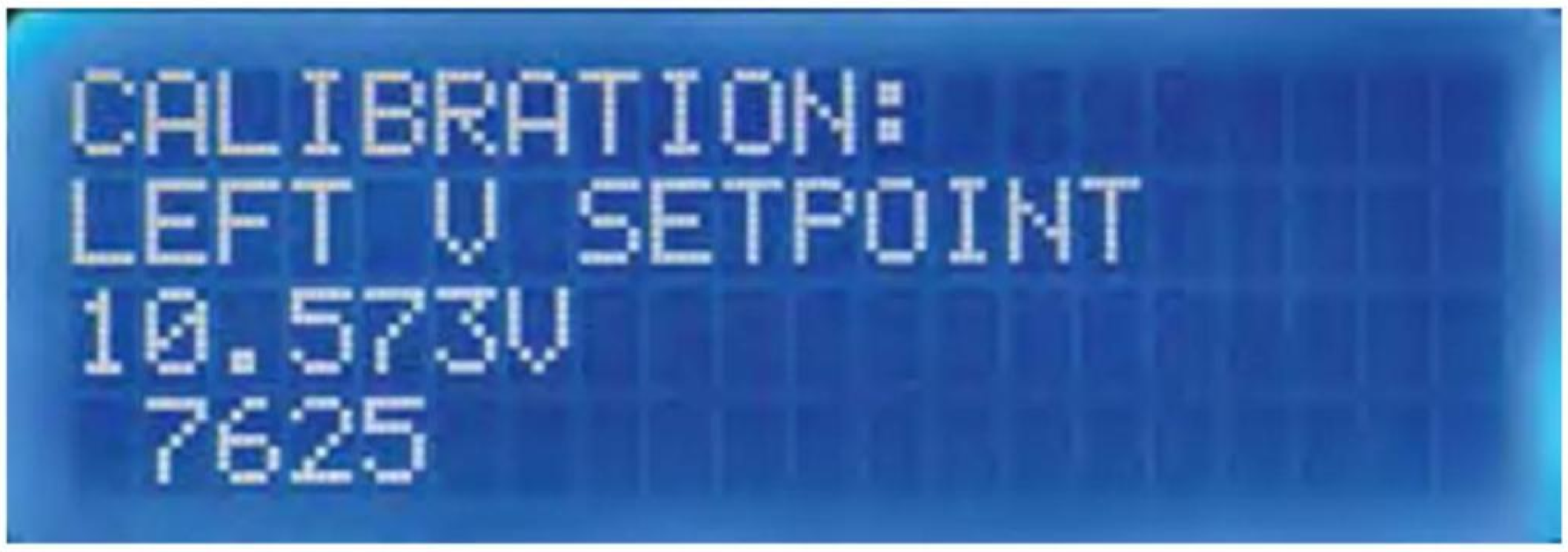
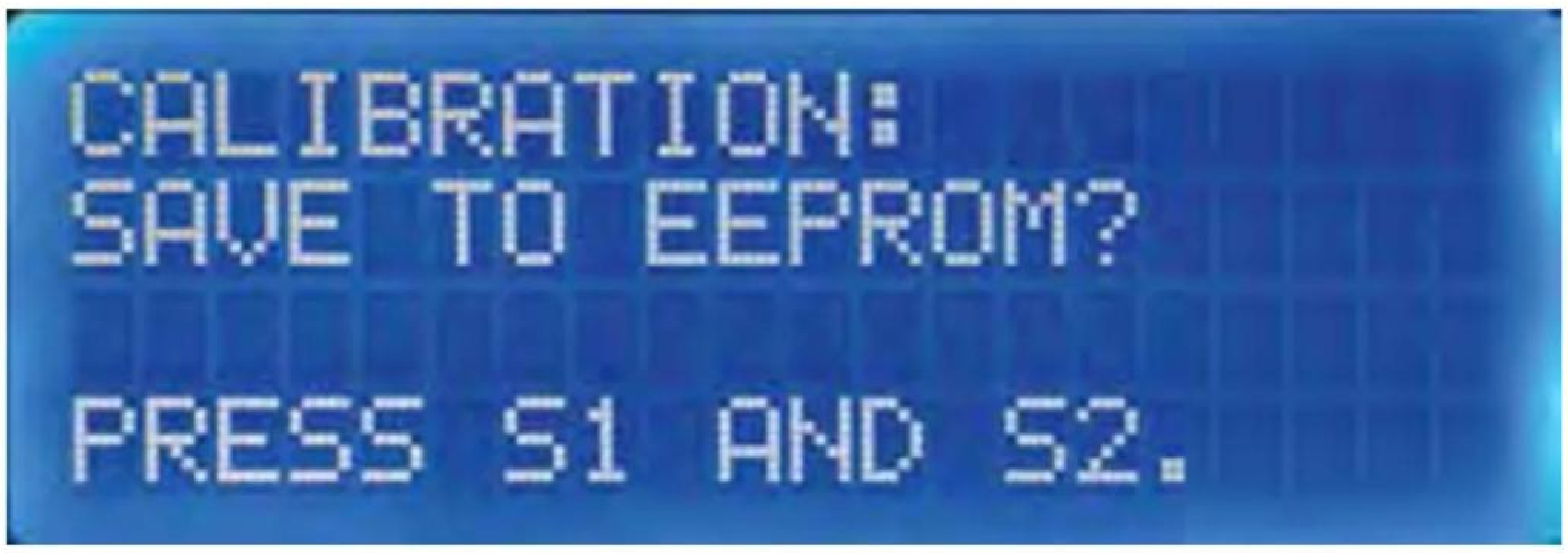
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator


```
CALIBRATION:
LEFT V SETPOINT
10.573V
 7625
```

Screen 2: all the main parameters shown on the main screen can be calibrated using these screens. Simply read off the actual voltage with a multimeter and use S1 and S2 to adjust the displayed voltage until it matches.


```
CALIBRATION:
SAVE TO EEPROM?

PRESS S1 AND S2.
```

Screen3: the calibration factors can be saved to non-volatile EEPROM by pressing S1 and S2 simultaneously on this page.

sure that current limiting is active to check the setpoints.

Select the appropriate screen, then adjust the calibration factor up or down using S1 and S2, respectively, until the multimeter reading matches the displayed reading.

Take care that you have the correct screen, as there are quite a few different parameters. After that, return to the main screen and check that the displayed values are consistent.

The final calibration page (Screen 3) allows the calibration factors to be saved to EEPROM, meaning they will be stored permanently for future use. Simply press S1 and S2 together on this page to permanently save the data. A message will be displayed to confirm this has happened.

Using it

From now, the Display Adaptor simply displays the various voltages and currents set and used by the Breadboard PSU. You can mute and unmute the alarms with S1 and S2.

The power display at lower right that alternates with the supply voltage will warn of conditions that might overheat the Breadboard PSU's transistors. The display reads 0W-9W for each channel, as that's all it can show in the available space. The design is intended to handle up to 3W continuously and up to 5W for short periods.

If you see these creeping up any higher, shut down the circuit to avoid damage to the Breadboard PSU.

With everything set up, you shouldn't need to do anything with the Display Adaptor except read what it displays.

On the main screen, S1 and S2 toggle the audible alarms for the CON3 and CON4 outputs, respectively. A speaker icon with an 'x' indicates that the alarm is muted, which is the power-up default.

Since LED1 sits above VR1 and LED2 sits above VR2, each LED corresponds to one channel of the Breadboard PSU. Usually, the green LED is lit for each channel. If IC4 detects that the actual voltage is not near the setpoint voltage, it changes the LED to red. In practice, this means that the current limiting has activated, although it can also happen if the voltage potentiometers are set above the DC input voltage.

If the alarm for the corresponding channel is not muted, the piezo sounds in short chirps when the corresponding LED is red. That should get your attention without being as annoying as if it sounded constantly.

While the Breadboard PSU lacks an on/off or load disconnect switch, it's quite easy to pull out the side plugged into the breadboard, which disconnects it. It would be a good idea to do that immediately, if you notice the transistor dissipation values are unexpectedly high or something else is wrong.

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NKT214F, OC57, OC59, 2N1377, 2N525	£1.00
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GET106	£2.50
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OC139, OC140, ASY73	£2.00
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TAA435 (Mullard power amp driver)	£1.20

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CA3086 transistor array	£1.00
PT2399 echo/delay	£1.50

Dual transistors

2N2639, 2N2223, 2N2910 (NPN)	£4.00
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2SK2145-Y dual JFET	£0.80
2N5564 JFET	£8.00
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Loudspeakers

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Morel MDT29 tweeter (each)	£25
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Monacor DT-28N tweeter (each)	£35
Vifa 19mm BC20SC15-04 tweeter (each)	£15
Volt crossover inductors	
1.2mH, 1.5mH, 2mH, 2.7mH, 0.5mH (tapped at 0.3mH) (each)	£5.85
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64mm 64Ω neodymium	£1.20
5x3-inch elliptical 50Ω or 80Ω Alnico	£3.50
1.65x2.75-inch 8Ω	£1.50

Capacitors

Note '10/63' denotes '10µF 63V'.

Polyester	
3.3/100, 4.7/250, 4.7/63	£1.00
5.6/63, 8.2/63, 10/63	£2.00
Mullard 'Mustard' C296 0.22/400	£2.00
Polycarbonate	
Axial 2.2/63 1%, 4.7/160, 6.8/63	£1.00
Radial	
6.8/160V, 10/63	£2.00
Reclaimed 22/63	£2.00
Polystyrene	
Philips 1% 4.7nF/160, 6.2nF/500, 12nF/63, 22nF/63, 110nF/63, 24nF, 2nF	£1.00
RIFA 1% 100nF/100, Suflex 90.9nF 0.5%	£2.00
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Siemens cellulose acetate MKL 2.2/25	£0.80
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10/25, 22/25, 100/10	£0.50
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5k Bourns 3321H cermet trimmer	£0.50

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Contact

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 12

I don't know about you, but our previous column (*PE*, November 2023) already seems like a lifetime away. Just to remind ourselves as to where we're at, we used the value read from our trimpot to control the *frequency* of segment D flashing on our 7-segment display. Next, for giggles and grins, we used the trimpot to control the *brightness* of segment D.

As usual, you can download an image of our current breadboard layout showing the switches, our trimpot, our piezoelectric buzzer, and our 7-segment display – along with various pull-up and current-limiting resistors – coupled with the connections to our Arduino Uno (file **CB-Dec23-01.pdf**). Also, as usual, all the files mentioned in this column are available from the December 2023 page of the *PE* website: **https://bit.ly/pe-downloads**

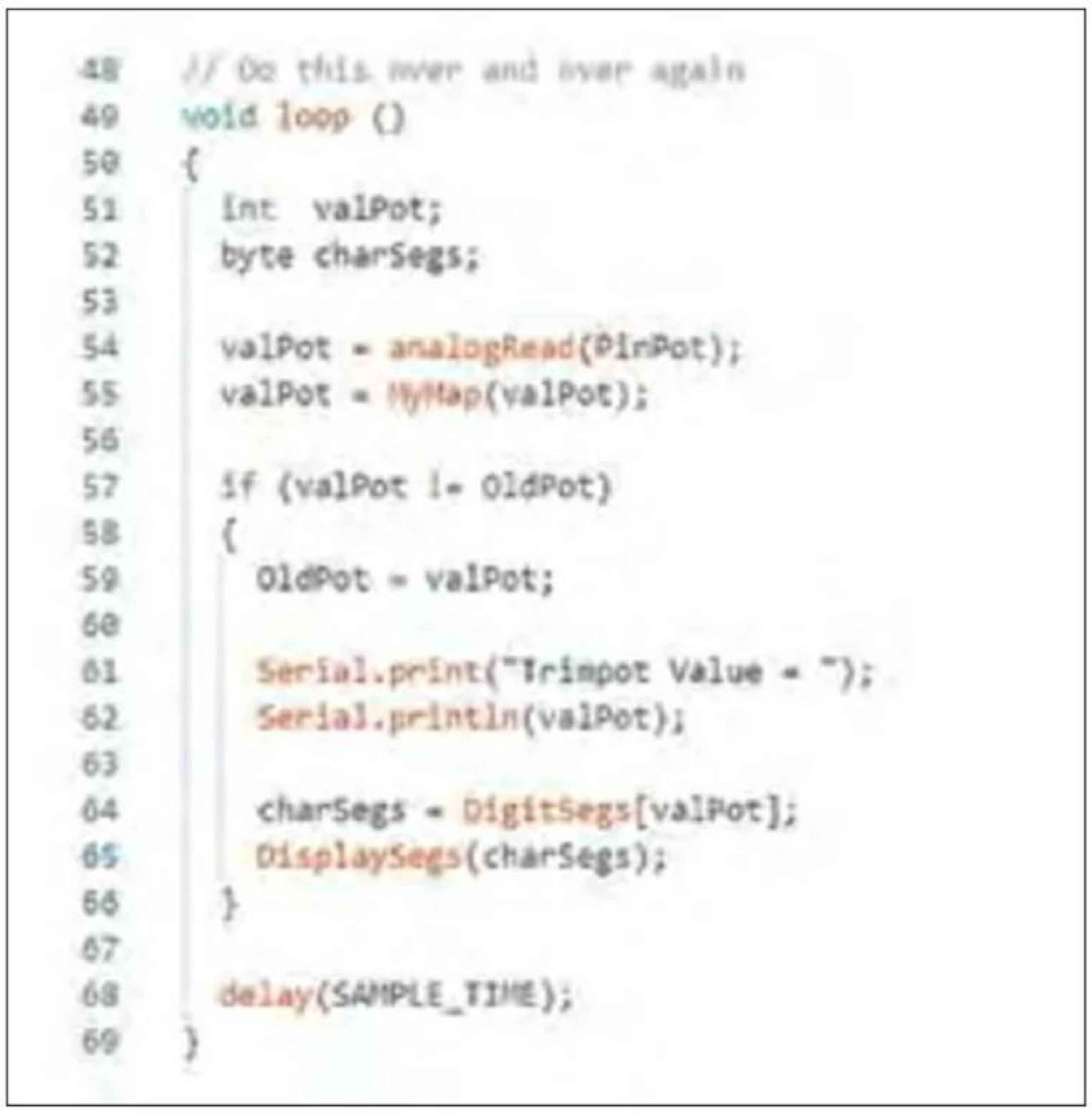
It hurts me to say…

This is going to hurt me more than it hurts you because I'm the one who is going to do all the work. As you may recall, we still have two of our homework assignments outstanding from our last-but-one column (*PE*, October 2023). The first is to map the 0 to 1023 input values read from our trimpot onto a range of 0 to 9 and – in addition to writing these values to the Serial Monitor – present them on our 7-segment display.

The great thing about this is that we've already created a bunch of little programs. What I'm going to do is root around our earlier offerings to find one that displays the digits 0 through 9. I'm also going to take one of the examples from our previous issue – the one that reads the 0 to 1023 values from our trimpot and uses our own mapping function to translate them into a 0 to 9 subset. I'm going to munge these two programs together, mix in a little magic, and see what happens. So, make yourself comfortable. I'll be back in just a moment.

There, that didn't take long, did it? You will be relieved to hear that this took only a couple of minutes and it works like a charm. You can download the resulting program (file **CB-Dec23-02.txt**) to peruse, ponder, and play with it at your leisure.

There's no need for us to show the whole program here. Suffice it to say that we start by defining a few useful values. Next, we declare a global integer called `PinPot` to which we assign the number of the analog input pin that's connected to our trimpot. We also declare a global array of integers called `PinsSegs[]` to which we assign the numbers of the eight digital pins we wish to use as outputs to drive our 7-segment display (remember that there's a decimal point segment in addition to the seven A through G segments). And, of course, we declare a global array of 8-bit bytes called `DigitSegs[]` to define which segments on the 7-segment display correspond to the decimal digits we wish to present. One more thing while I'm thinking about it is that we declare a global integer called `OldPot` ('old value from the trimpot') to which we assign a value of –1 (we use –1 as an initial value because this isn't something we will ever see from our trimpot).



```
48  // Do this over and over again
49  void loop ()
50  {
51    int  valPot;
52    byte charSegs;
53
54    valPot = analogRead(PinPot);
55    valPot = MyMap(valPot);
56
57    if (valPot != OldPot)
58    {
59      OldPot = valPot;
60
61      Serial.print("Trimpot Value = ");
62      Serial.println(valPot);
63
64      charSegs = DigitSegs[valPot];
65      DisplaySegs(charSegs);
66    }
67
68    delay(SAMPLE_TIME);
69  }
```

Listing 2a. Our new `loop()` function.

In addition to the `setup()` and `loop()` functions, we have only two of our own functions. The first, `MyMap()`, is the one we created in our previous column to map the 0 to 1023 values from the trimpot to the desired 0 to 9 subset. The second, `DisplaySegs()`, is our old friend that we use to turn the various display segments on and off to represent the decimal digits 0 through 9.

The main function of interest to us here is `loop()`, as illustrated in Listing 2a. (Following some confusion associated with my previous column, we're using a new scheme in which the listing number (Listing 2 in this example) corresponds to the associated program file (**CB-Dec23-02.txt** in this example), and then we'll use 'a', 'b', 'c'… as suffixes, as appropriate).

We start on Line 51 by declaring a local integer variable called `valPot` ('value from the trimpot'). On Line 52 we declare a local 8-bit byte variable called `charSegs` ('character segments').

On Line 54 we read a value of 0 to 1023 from the trimpot and load it into `valPot`. On Line 55 we call our `MyMap()` function to convert this value into our 0 to 9 subset.

We perform a test on Line 57 to see if this new value is different (not equal) to the old one (this test will definitely return `true` the first time we pass through the loop because of the –1 value with which we initialised `OldPot`). If so, we execute the statements in the block defined by the `{` and `}` curly brackets on Lines 58 and 66. First, on Line 59, we copy the new local mapped value from the trimpot into the old global value so we'll remember it the next time we pass through the loop. Second, on Lines 61 and 62, we output the trimpot value to the Serial Monitor. And third, on Lines 64 and 65, we light up the appropriate segments on our 7-segment display.

You may be wondering about the call to the `delay()` function on Line 68 (I've defined `SAMPLE_TIME` as being 100 milliseconds (ms), or 1/10th of a second). On the other hand, you may not have even noticed it. Whichever, now that I've brought it to your attention, why do you think I included this little scamp?

Well, the thing is, even though the Arduino Uno's clock is running at only 16MHz, which is slow for a microcontroller these days, that's still 16 million cycles per second. What this means is that, if left unchecked, the Uno will sample the value from the trimpot multiple times as we cross the boundary equating to one of our 0 to 9 mapped values to another.

This wouldn't be a problem if `valPot` transitioned smoothly from one value to another, but it typically doesn't because the values being read from the trimpot are inherently noisy. As a result, rather than our mapped value transitioning cleanly from …5 5 5 to 6 6 6…, for example, what we will usually see is a transition more along the lines of …5 5 5 **6 5 6 5** 6 6 6… which is a tad annoying. You can watch it happening on your own rig by deleting Line 68 or by changing the value associated with `SAMPLE_TIME` to 0. The bottom line is that including a 100ms sample time gives the trimpot – and hence the value on `valPot` – time to firmly transition from one value to the next.

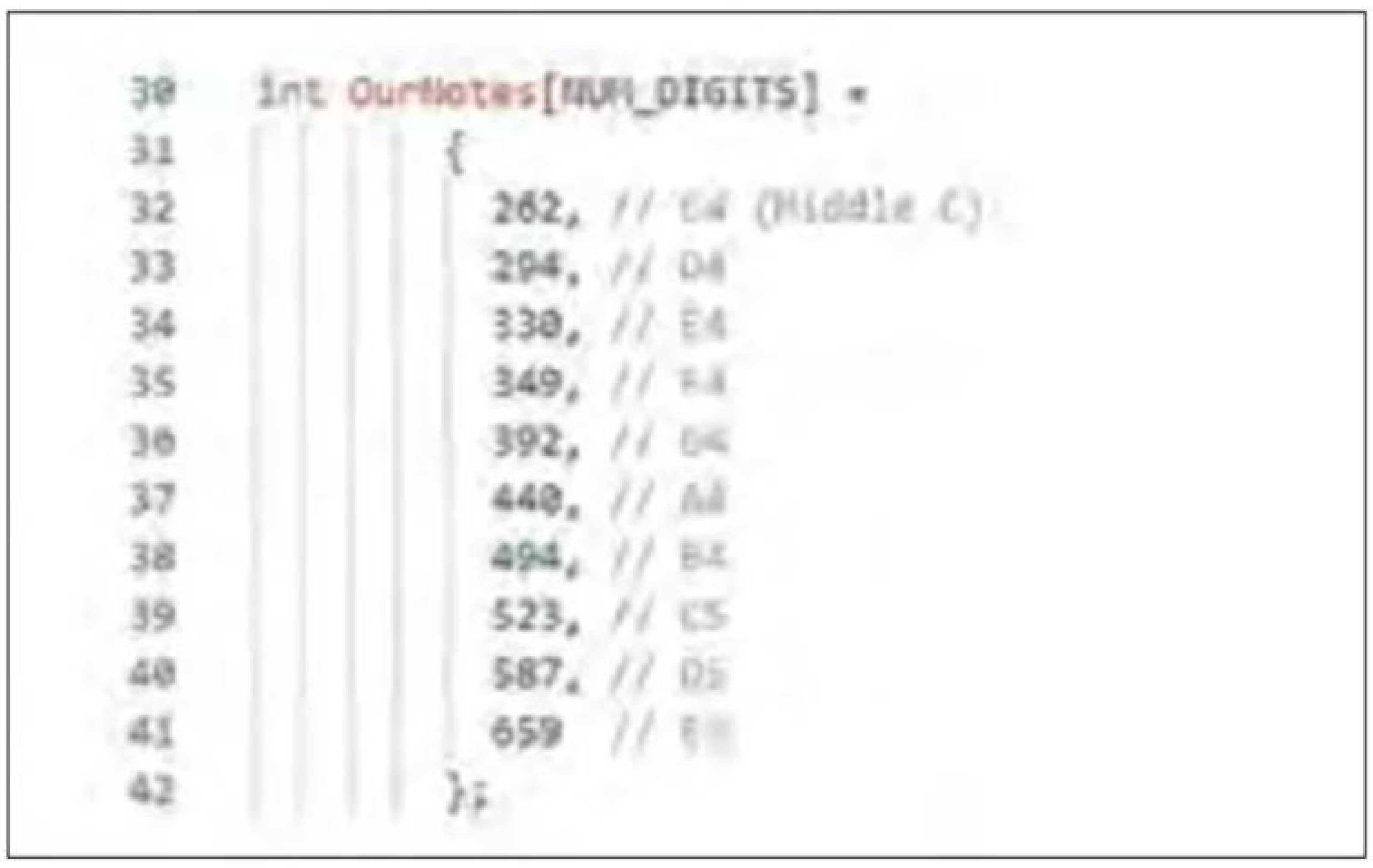
I don't know about you, but as I've mentioned before, even though this is really very simple stuff, I still get a buzz of excitement when I rotate my trimpot and I see my 7-segment display respond.

You hum it son…

Do you remember the TV adverts for PG Tips tea bags featuring anthropomorphic chimpanzees wearing human clothes with dubbed voices provided by celebrities, such as Peter Sellers, Donald Sinden and Bob Monkhouse? One of these adverts featured two of the chimpanzees moving a piano. The younger one says, 'Dad, do you know the piano's on my foot?' The father replies, 'You hum it son, and I'll play it!'

All of which serves as smooth a segue as you might wish into our final homework assignment, which was to augment the program we just created to also cause our piezo-electric buzzer to play one of ten musical notes, with 0 corresponding to middle C (that's C4 in scientific pitch notation).

How are we going to do this? Well, a good starting point is to decide which notes we wish to play. If we are going to *exclude* sharps and flats, then our 0 to 9 values will correspond to C_4, D_4, E_4, F_4, G_4, A_4, B_4, C_5, D_5, and E_5, respectively. Alternatively, if we decide to *include* sharps and flats, then our 0 to 9 values will correspond to C4, CS4, D4, DS4, E4, F4, FS4, G4, GS4, and A4, respectively, where the 'S' characters stand for 'sharp,' and F# (F sharp) is the same as G♭ (G flat), for example. We need to pick one or the other, so I'm going to adopt the former scheme.



```
int OurNotes[NUM_DIGITS] =
          {
            262, // C4 (Middle C)
            294, // D4
            330, // E4
            349, // F4
            392, // G4
            440, // A4
            494, // B4
            523, // C5
            587, // D5
            659  // E5
          };
```

Listing 3a. Array of note frequencies.

The next step is to determine which frequencies are associated with each of the notes. For this, I turned to a super-useful book called *Exploring Arduino*, Second Edition, by Jeremy Blum, see: **https://bit.ly/3LYAbOJ**

For the purposes of this column, *Chapter 6: Making Sounds and Music*, is of particular interest, not least because of the code examples we can download from his Exploring Arduino website, especially the page for *Chapter 6* – see: **https://bit.ly/3PXTtEY**

Once you have safely arrived there, click the 'Download Code' button, and you are presented with a compressed ZIP file. One of the files contained within is called **pitches.h** (I've provided a text version for your delectation and delight – file **pitches.txt** – which you can rename to **pitches.h** and then include in your programs as a header file if you wish, but we aren't going to do that here).

From this file, we learn that the frequencies associated with our chosen set of notes are as follows:

C4	262Hz
D4	294Hz
E4	330Hz
F4	349Hz
G4	392Hz
A4	440Hz
B4	494Hz
C5	523Hz
D5	587Hz
E5	659Hz

As an aside, C or 'Do' (as in *Do Ray Me Fa So La Ti Do*) is the first note and semitone of the C major scale Do you remember the classic flashmob singing of the *Do Ray Me* song in Antwerp train station? – see: **https://bit.ly/3PWYhdN**

It's interesting to note that the actual frequency of C_4 has depended on historical pitch standards. According to Wikipedia, for example, 'For an instrument in equal temperament tuned to the A440 pitch standard widely adopted in 1939, middle C has a frequency around 261.63Hz.' As we see, Jeremy has rounded his values to the nearest integer.

Also of interest is the fact that, for some purposes, a convention may be adopted in which the frequencies of the various Cs are powers of two. In this case, the frequency of middle C would be said to be 256Hz. But we digress…

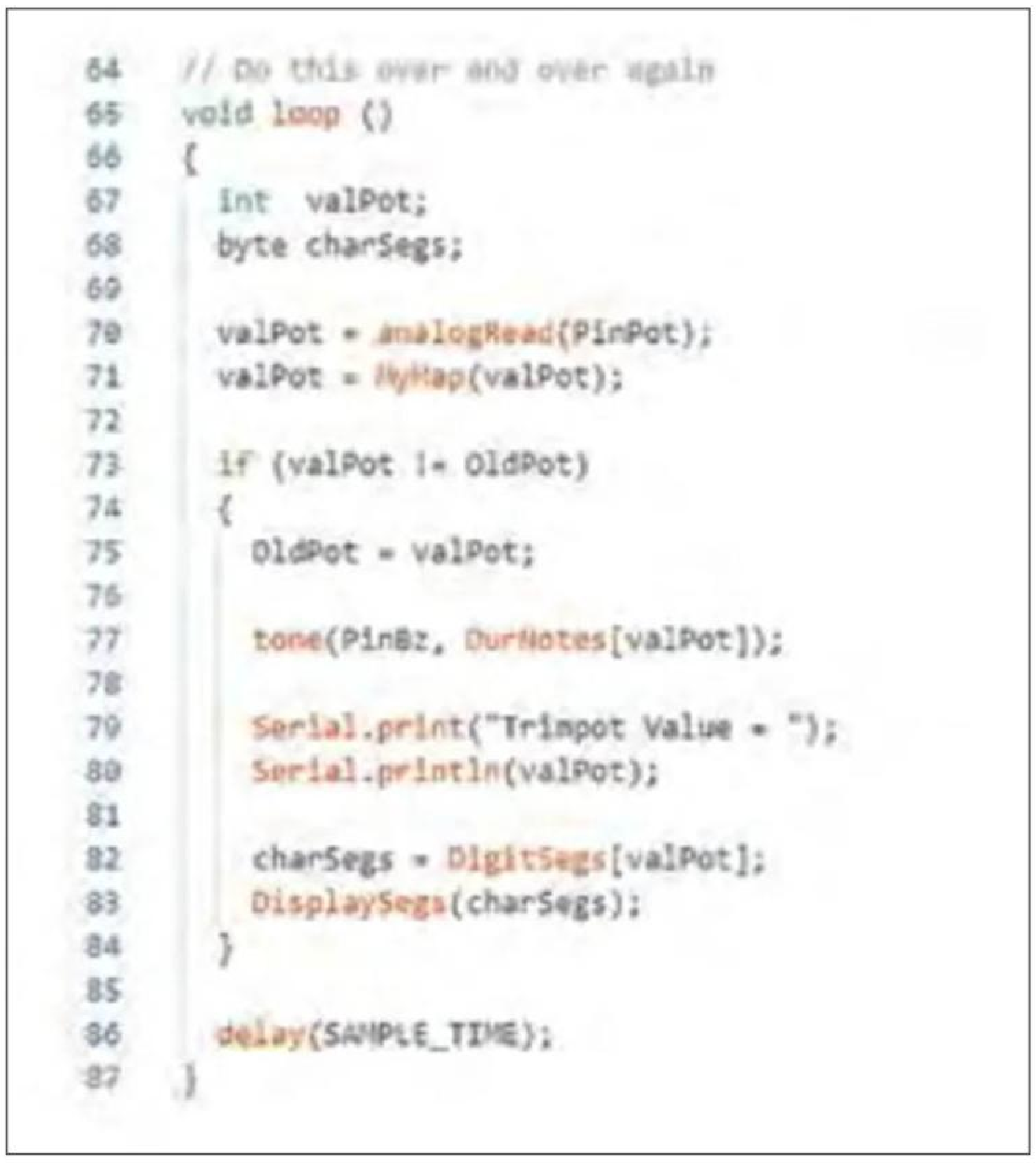
Take a note

For some reason I'm envisaging the Welsh prop comedian and magician Tommy Cooper saying, 'Take a note... any note… but don't let me see which one.' I'm also remembering the English comedian Eric Morcombe saying to his sidekick Ernie Wise, 'I *am* playing all of the notes… just not necessarily in the right order is all.'

In the context of software development, the term 'fork' refers to taking the source code for an existing project and using it to create a new application based on the original code. So, to add sounds to our code, we're going to fork the program we created earlier, after which we will edit the forked version (file **CB-Dec23-03.txt**).

The first thing we will do, for reasons that will become apparent, is to change the value associated with `SAMPLE_TIME` to 250 (that is 250ms, 1/4 of a second). Next, we will declare a global integer called `PinBz`, to which we assign the number of the digital pin we are using to drive our piezoelectric buzzer. As part of this, we will add a `pinMode()` statement to our `setup()` function to inform our Arduino Uno that we want to use this pin as an output.

Also, we will declare a global array of integers called `OurNotes[]` containing the ten frequency values associated



```
64  // Do this over and over again
65  void loop ()
66  {
67    int  valPot;
68    byte charSegs;
69
70    valPot = analogRead(PinPot);
71    valPot = MyMap(valPot);
72
73    if (valPot != OldPot)
74    {
75      OldPot = valPot;
76
77      tone(PinBz, OurNotes[valPot]);
78
79      Serial.print("Trimpot Value = ");
80      Serial.println(valPot);
81
82      charSegs = DigitSegs[valPot];
83      DisplaySegs(charSegs);
84    }
85
86    delay(SAMPLE_TIME);
87  }
```

Listing 3b. First modification to `loop()`.

with the notes C4 through E5. Noting that `NUM_DIGITS` has been defined as 10, this array is shown in Listing 3a.

Happily for us, the Arduino supports a built-in function called `tone()` that we can use to play notes using our piezo buzzer. There's also a corresponding `noTone()` function. There are two ways to call the `tone()` function and one way to call the `noTone()` function as follows:

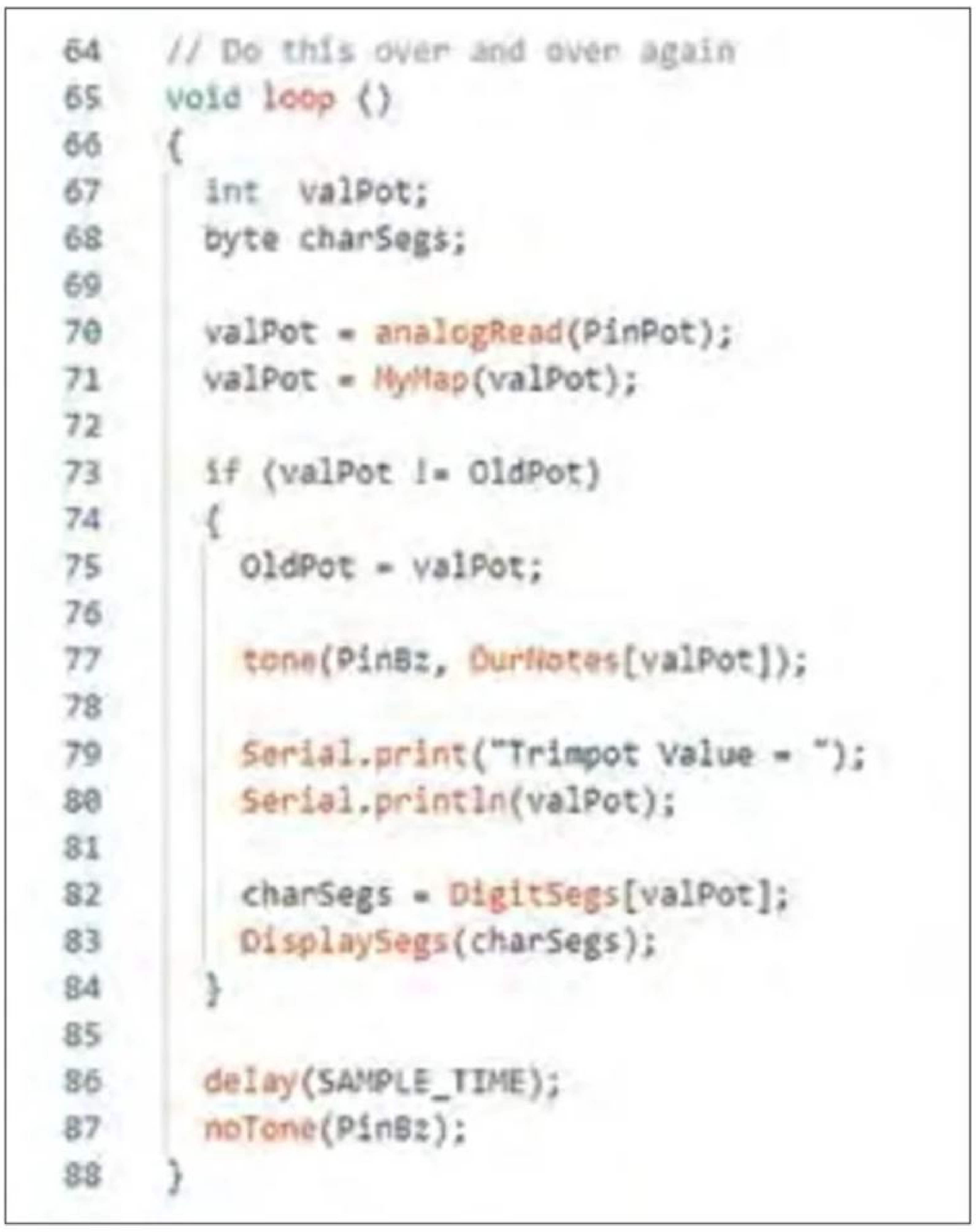
```
tone(pin, frequency);
tone(pin, frequency, duration);

noTone(pin);
```

The `pin` is the Arduino pin on which we wish to generate the tone (the pin connected to our piezo buzzer in our case). The `frequency` is the frequency of the desired tone in hertz. The `duration` is the duration of the tone in milliseconds. If this last argument is omitted, the note will continue to play until a new call to the `tone()` function changes the frequency or a call to the `noTone()` function terminates the note.

There are various considerations involved with the `tone()` function, such as the fact that it will interfere with the Arduino Uno's pulse-width modulated (PWM) outputs on pins 3 and 11, so I strongly recommend you take a look at the *Arduino Reference Guide* for this function before you use it for anything other than the examples shown here – see: **https://bit.ly/46wGvoQ**

Last, but not least, we need to modify our `loop()` function as shown in Listing 3b. As we see, all we need do is add a call to the `tone()` function on Line 77, employing the same `valPot` value we are using to control the 7-segment display to index into our `OurNotes[]` array of frequencies.

I just tried running my original version of this program. Unfortunately, the constantly playing tones acted like a siren song to our two stupid cats, who came to see what was happening and subsequently attempted to rearrange the components on my breadboard. I could have added a duration argument to the call to the `tone()` function. As an alternative, just to show this in action, I added a call to the `noTone()` function on Line 87 of the `loop()` function, as shown in Listing 4a (file **CB-Dec23-04.txt**).



```
64  // Do this over and over again
65  void loop ()
66  {
67    int  valPot;
68    byte charSegs;
69
70    valPot = analogRead(PinPot);
71    valPot = MyMap(valPot);
72
73    if (valPot != OldPot)
74    {
75      OldPot = valPot;
76
77      tone(PinBz, OurNotes[valPot]);
78
79      Serial.print("Trimpot Value = ");
80      Serial.println(valPot);
81
82      charSegs = DigitSegs[valPot];
83      DisplaySegs(charSegs);
84    }
85
86    delay(SAMPLE_TIME);
87    noTone(PinBz);
88  }
```

Listing 4a. Second modification to `loop()`.

This is why we increased the `SAMPLE_TIME` value to 250 earlier. Now, when we rotate our trimpot, every time we transition to a new value, we receive a quarter-second note followed by glorious cat-free silence.

Reinventing the wheel

In a moment we are going to be talking about power, so let's briefly refresh our memories. One equation of interest here is $P = V \times I$, where P is power (measured in watts), V is voltage (measured in volts), and I is current (measured in amps). Also, from Ohm's law (which we introduced in *PE*, January 2023), we know that $V = I \times R$, where R is resistance measured in ohms (symbol Ω).

This means we can quickly calculate P, V, I, and R so long as at least two of the values are known. There's a very useful

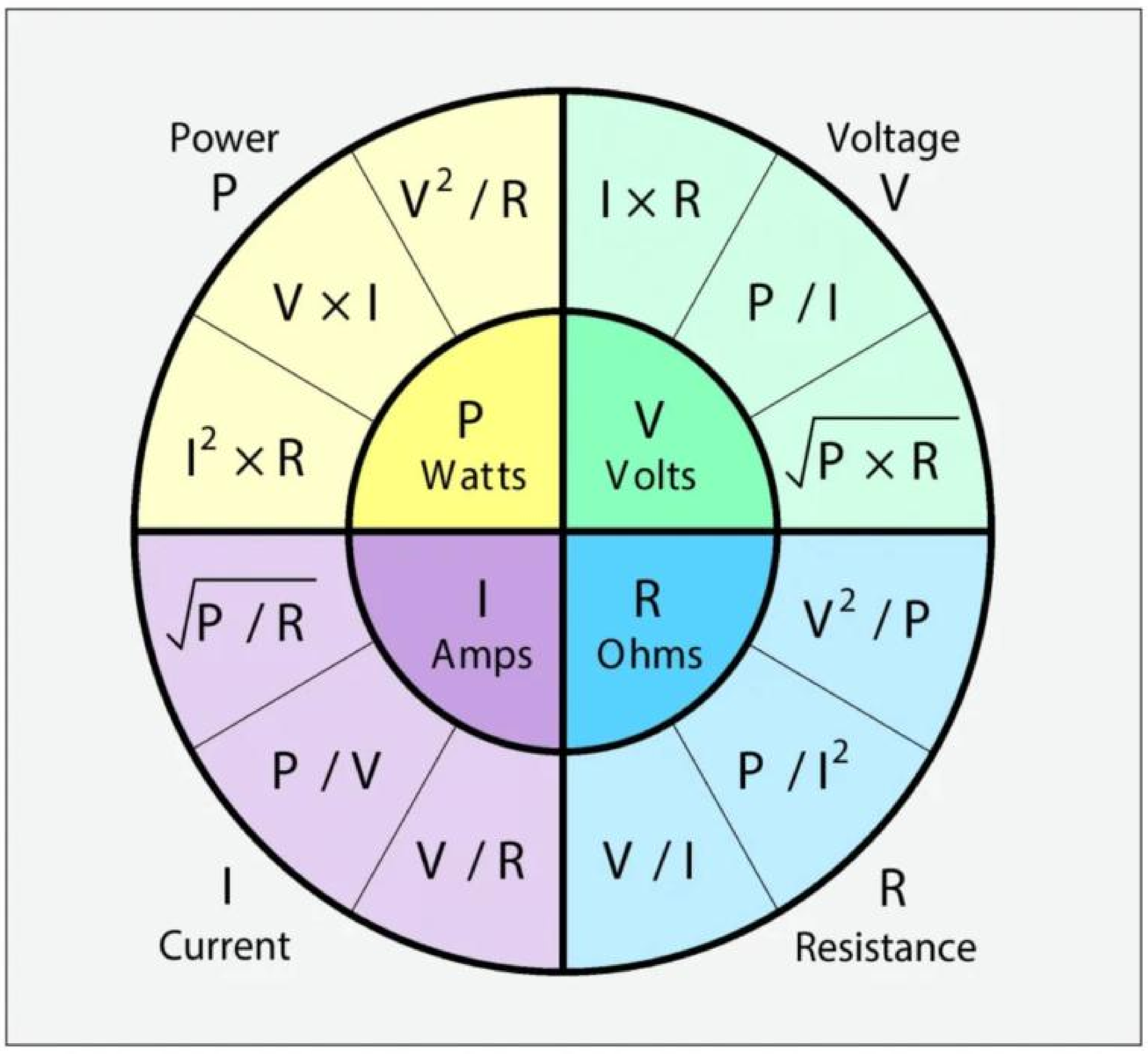


Fig.1. Ohm's law wheel.

visual representation of this called Ohm's wheel or Ohm's law wheel (Fig.1).

Anything but futile

If you're a fan of Star Trek, you'll understand the phrase 'Resistance is Futile' to mean 'Don't bother resisting because we'll overtake you.' This was the way the Borg – cybernetic organisms linked in a hive mind – preferred to say 'Hello.' Of course, it didn't take long before electronics engineers started sporting T-Shirts with a resistor symbol accompanied by the text 'IS FUTILE' (to know us is to love us).

In reality, of course, resistance is anything but futile because it can be used for all sorts of things, including sensors whose resistive values vary as a function of whatever it is they are intended to measure.

Take temperature, for example. All resistors change their value as a function of temperature. This isn't something we typically favor. Why? Well, apart from the fact that – in the usual course of events – we would prefer the values of our components to remain constant, the higher the current flowing through a resistor, the hotter it gets, which increases its resistance, which causes it to get even hotter. If a resistor gets sufficiently hot, then – much like the Norwegian Blue in Monty Python's *Dead Parrot* sketch – it won't be long before you find yourself the proud possessor of an ex-resistor which has 'joined the choir invisible' – see: **https://youtu.be/4vuW6tQ0218**

This is why it's important to stay within the resistor's wattage rating. When the resistor is operating within its power rating, any heat is dissipated into the surrounding environment. If the resistor's power rating is exceeded, it won't be able to dissipate the excess heat, and… poof!

Let's take a moment to think about the resistors on our breadboard. These are 1/4W (0.25 watt) devices. The resistors we decided to use with our switches are 10kΩ parts. Since we are running at 5V, from Ohm's wheel we can use $P = V^2 / R$ to determine that the power being dissipated by these resistors is (5 × 5) / 10,000 = 0.0025W, which is 1/100th their rated value.

As we discussed earlier in this series (*PE*, February 2023), in the case of our 7-segment display, the forward voltage drop of the red light-emitting diode (LED) segments is approximately 2V, which means our current-limiting resistors are dropping 5V – 2V = 3V. We don't need to know the value of these resistors here (we do know them, but we don't need to) because we selected this value to meet the maximum forward current of the LEDs, which is 20mA. Since we know the voltage (3V) and the current (0.02A), we can use $P = V \times I$ from Ohm's wheel to determine that the power being dissipated by these resistors is 3 x 0.02 = 0.06W, which is approximately a quarter of their rated value.

Moving on… a thermistor (a portmanteau of 'thermal' and 'resistor') is a semiconductor-based type of resistor whose resistance value is strongly dependent on temperature – much more so than in standard resistors. This means that, once we've calibrated things, we can use these devices to measure temperature.

We aren't going to play with thermistors here because we have other *poisson à frire* (fish to fry). If you do decide to experiment with these devices in the future, you need to be aware that they come in two flavors: those with a negative temperature coefficient (NTC), in which the resistance *decreases* as the temperature increases, and those with a positive temperature coefficient (PTC), in which the resistance *increases* as the temperature increases.

Blinded by the light

Another very useful sensor is a photoresistor, which is also commonly known as a light-dependent resistor (LDR). This is a semiconductor-based type of resistor whose resistance value *decreases* as the ambient light intensity *increases* (see Fig.2).

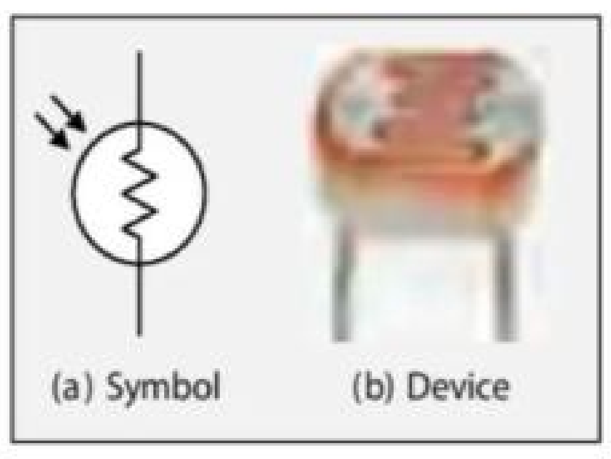


Fig.2. An LDR, aka a light-dependent resistor – these are easy-to-use non-polarised devices.

Type	Dark resistance (MΩ)	Light resistance (kΩ) (10 lux)
GL5506	0.2	2 to 5
GL5516	0.5	5 to 10
GL5528	1	10 to 20
GL5537	2 to 3	20 to 50
GL5539	5	50 to 100
GL5549	10	100 to 200

Fig.3. Comparison of LDR types.

In the dark, an LDR can have a resistance as high as several megaohms (MΩ). As the light intensity increases, the LDR's resistance can fall to be as low as a few hundred ohms. Since I usually like to play with things, I opted for a 70-piece kit containing ten each of the following LDRs: GL5506, GL5516, GL5528, GL5537, GL5539, GL5549, and MG45. A similar kit is available from Amazon in the UK for around £16 – see: **https://bit.ly/3S2430m**

So, which of these LDRs should we use? I had a 'fun time' Googling this question (yes, that was my sarcastic voice). The fun only increased when I found different sources proffered different values for these devices. Also, there appear to be two flavors of the GL5537, and I couldn't find any information whatsoever on the MG45. To save you the pain, a rough and ready comparison is presented in Fig.3.

It takes only a brief glance at this table to realise that these LDR values are all over the place. Two LDRs of the same type may present very different resistance values for the same level of ambient light. What this means is that we typically need to calibrate our code to work with the LDR we are using. Also, their 'sloppy' nature means we usually employ LDRs to perform only relatively simple On/Off (Go/No-Go) type functions. There are more precise light-detecting devices available – like photodiodes and phototransistors – but LDRs will serve our purpose here.

As discussed in our previous column, if you have a clock with an LED display in your bedroom then – assuming you didn't buy the cheapest one going – when you turn off the lights, the clock will sense this and reduce the brightness of its display. In this case, it will probably be using an LDR to perform this sensing function.

I recently saw a circuit intended to automatically close window blinds when it got dark outside and open them again when the outside light returned. To provide hysteresis (which we might take to mean 'slowing the response to changes in the stimulus,' in this example), this circuit employed two LDRs – one to detect when the outside light fell *below* a certain level and the other to detect when the light rose *above* a certain level.

One of the great things about electronics is that there are always multiple ways of doing the same thing (or, at least, of achieving the desired goal). Contrariwise, one of the things about electronics that can make your head hurt is that there are always… you get the idea.

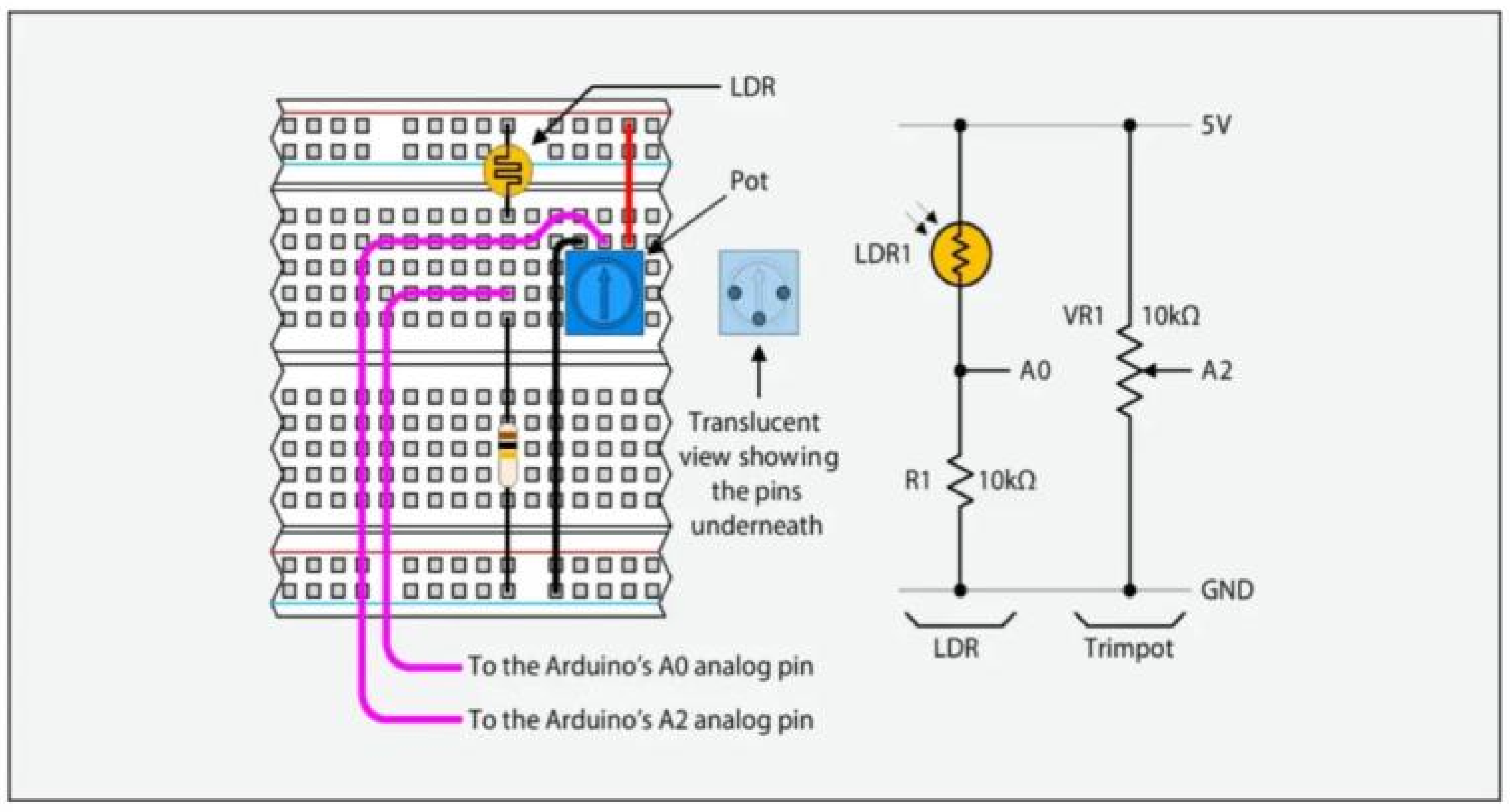

LDR
Pot
Translucent view showing the pins underneath
To the Arduino's A0 analog pin
To the Arduino's A2 analog pin
5V
LDR1
VR1
10kΩ
A0
A2
R1
10kΩ
GND
LDR
Trimpot

Fig.4. Adding an LDR to our breadboard.

Components from Part 1

LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk

Components from Part 2

7-segment display(s)	https://amzn.to/3Afm8yu

Components from Part 5

Momentary pushbutton switches	https://amzn.to/3Tk7Q87

Components from Part 6

Passive piezoelectric buzzer	https://amzn.to/3KmxjcX

Components for Part 9

SW-18010P vibration switch	https://bit.ly/46SfDA4

Components for Part 10

Breadboard mounting trimpots	https://bit.ly/3QAuz04

Components for Part 12

Light-Dependent Resistor	https://bit.ly/3S2430m

Adding an LDR

I don't know about you, but my breadboard is starting to look a little cluttered, so I've decided to remove my two pushbutton switches and their associated pull-up resistors (I can always add them back later) and replace them with one of my LDRs along with a 10kΩ resistor (Fig.4). I'm going to use a GL5516 LDR because… well, why not?

LDRs are non-polarised components, which means that – like standard resistors – it doesn't matter which way round they are connected. You can download an image of the entire breadboard (file **CB-Dec23-05.pdf**).

As we see, we are using the LDR in conjunction with the 10kΩ resistor to form a potential divider, the nitty-gritty details of which we introduced in an earlier column (*PE*, October 2023).

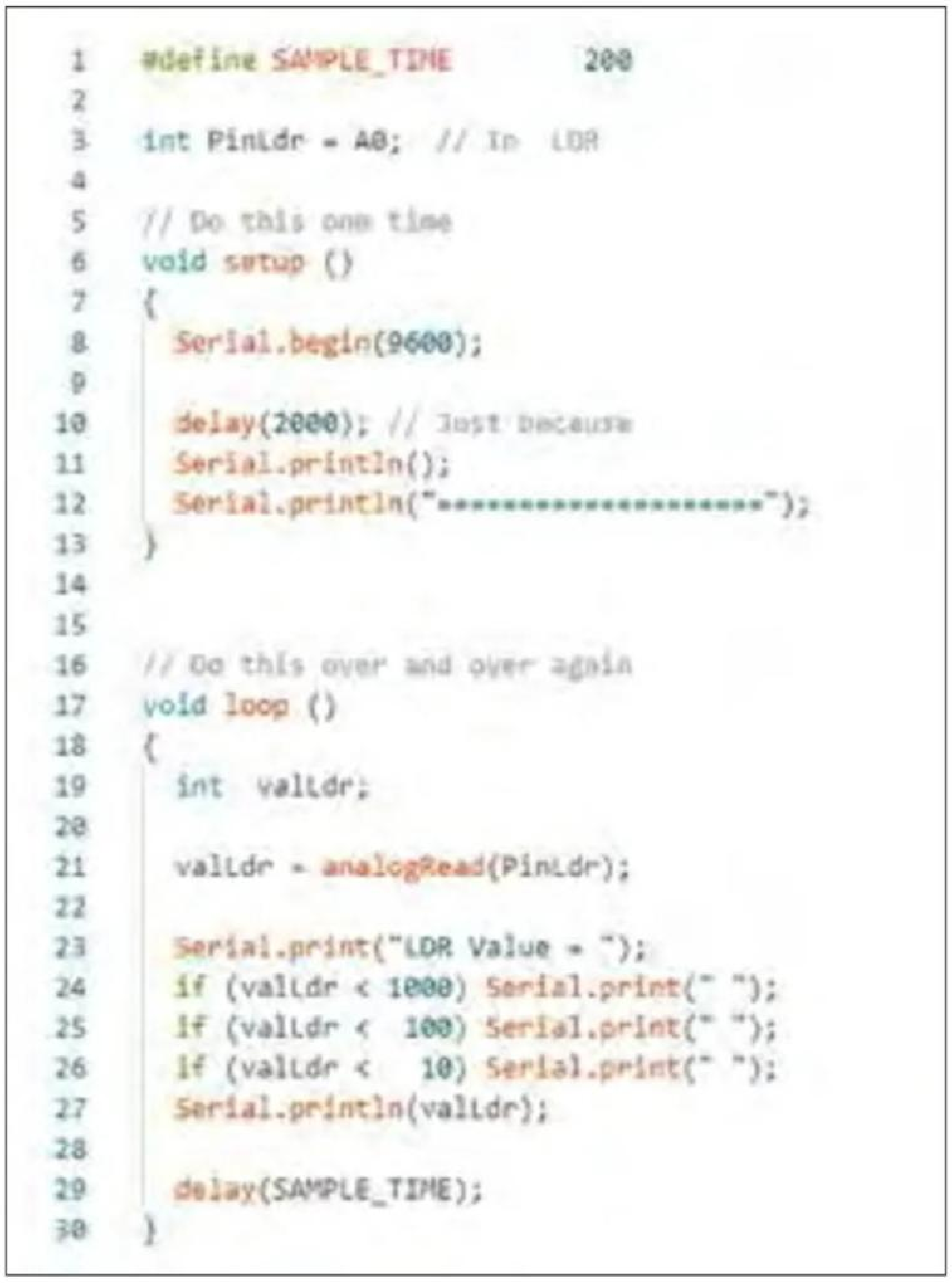
In this case, we've connected the 10kΩ resistor on the ground (0V) side and the LDR on the 5V side. Let's perform a little thought experiment. Suppose our LDR is in the dark, which means it will present its maximum resistance of 0.5MΩ. In this case, the voltage presented to Arduino input A0 can be calculated as the input voltage (5V) multiplied by (R1 / (R1 + LDR1)), which equates to 5V × (10,000 / (10,000 + 500,000)) = ~0.1V. In turn, this will equate to ~21 out of the 0 to 1023 range that can be generated by the Arduino's 10-bit analogue-to-digital converter (ADC).

Now suppose the LDR is exposed to a bright light that causes it to present its minimum resistance. Let's use the worst-case value of 5kΩ for the GL5516 from Fig.3. In this case, the voltage presented to the Arduino input A0 can be calculated as 5V × (10,000 / (10,000 + 5,000)) = ~3.3V. In turn, this will equate to ~675 when we read it into the Arduino.

It's worth noting that we could exchange the positions of the LDR and the 10kΩ resistor such that the LDR was on the 0V side and the 10kΩ resistor was on the 5V side. In this case, exposing the LDR to dark would cause the values seen by the Arduino to rise, while exposing the LDR to light would cause the values seen by the Arduino to fall.

Lighting up our LDR

Are you feeling feisty? Me too! Let's create a little program (Listing 6a) to see how well the real world matches up with our thought experiment (file **CB-Dec23-06.txt**).



```
1   #define SAMPLE_TIME         200
2
3   int PinLdr = A0;  // In  LDR
4
5   // Do this one time
6   void setup ()
7   {
8     Serial.begin(9600);
9
10    delay(2000); // Just because
11    Serial.println();
12    Serial.println("********************");
13  }
14
15
16  // Do this over and over again
17  void loop ()
18  {
19    int  valLdr;
20
21    valLdr = analogRead(PinLdr);
22
23    Serial.print("LDR Value = ");
24    if (valLdr < 1000) Serial.print(" ");
25    if (valLdr <  100) Serial.print(" ");
26    if (valLdr <   10) Serial.print(" ");
27    Serial.println(valLdr);
28
29    delay(SAMPLE_TIME);
30  }
```

Listing 6a. Testing the LDR.

All we are doing is looping around reading values from the LDR (Line 21) and writing those values to the Serial Monitor (Line 27). Line 23 is just 'for show,' while Lines 24, 25, and 26 ensure the values we display in the Serial Monitor are right aligned (we first used this technique in *PE*, October 2023).

Well, that was interesting

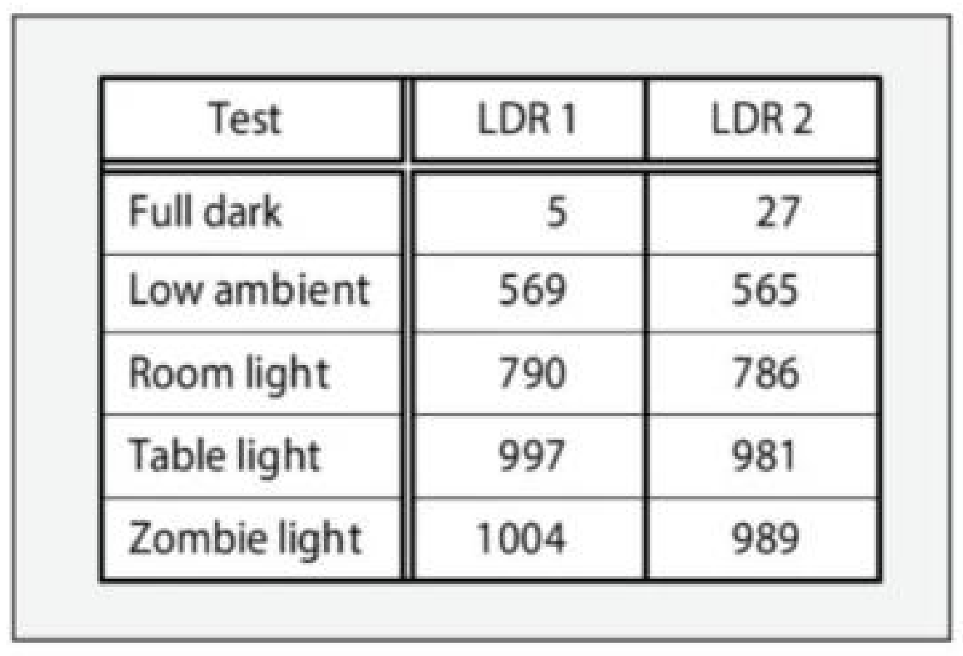
I just performed a very unscientific experiment as summarised in Fig.5. I placed my first LDR (LDR 1 in Fig.5) in full darkness (I put a tiny cardboard box over it). In this case, the values I saw hovered around 5, which was a little lower than we predicted.

My 'Low Ambient' test involved removing the box to expose the LDR and turning the room lights off. It's a dark gray late afternoon outside as I pen these words, and most of the light in the room is coming from my computer monitor, so I was a tad surprised to see readings hovering around 569.

Next, I turned the room light on in the center of the ceiling. This isn't all that bright because it boasts only four Edison Bulbs. 'Still and all,' as they say, the readings jumped up to hover around 790.

Turning on a small bendy-neck table lamp directly over the LDR caused the readings to jump up to around 997. Finally, I whipped out the trusty tactical LED flashlight (torch) I always carry about my person in case a Zombie apocalypse breaks out. This is super bright, but it caused only a small rise in the values coming from the LDR.

All this tells us several things, including the fact that the LDR's 'Dark Resistance' is significantly higher than 0.5MΩ, while its 'Light Resistance' is significantly lower than 5kΩ (I can't be bothered to do the maths). It's also



Test	LDR 1	LDR 2
Full dark	5	27
Low ambient	569	565
Room light	790	786
Table light	997	981
Zombie light	1004	989

Fig.5. Testing two LDRs.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

clear that the LDR saturates around the table light level, after which increasing the amount of light has little effect.

Out of interest, I swapped my existing LDR for another of the same type (shown as LDR 2 in Fig.5). To be honest, the most surprising thing to me here was that the results from the two devices matched each other so closely.

If a were a better man, I would test all 10 of my GL5516 LDRs, and then perform the same tests on the other LDR types. Sad to relate, I'm not a better man. Also, my wife (Gina the Gorgeous) is champing at the bit because she feels I should be spending 'quality time' with her as opposed to experimenting with an LDR ('significant others,' what can you say?).

Next time

In my next column, among myriad other things, we are going to use the values read from our LDR to control the brightness of our 7-segment display. Do you have any thoughts on how we will achieve this? I will leave you pondering this poser. Until next time, have a good one!

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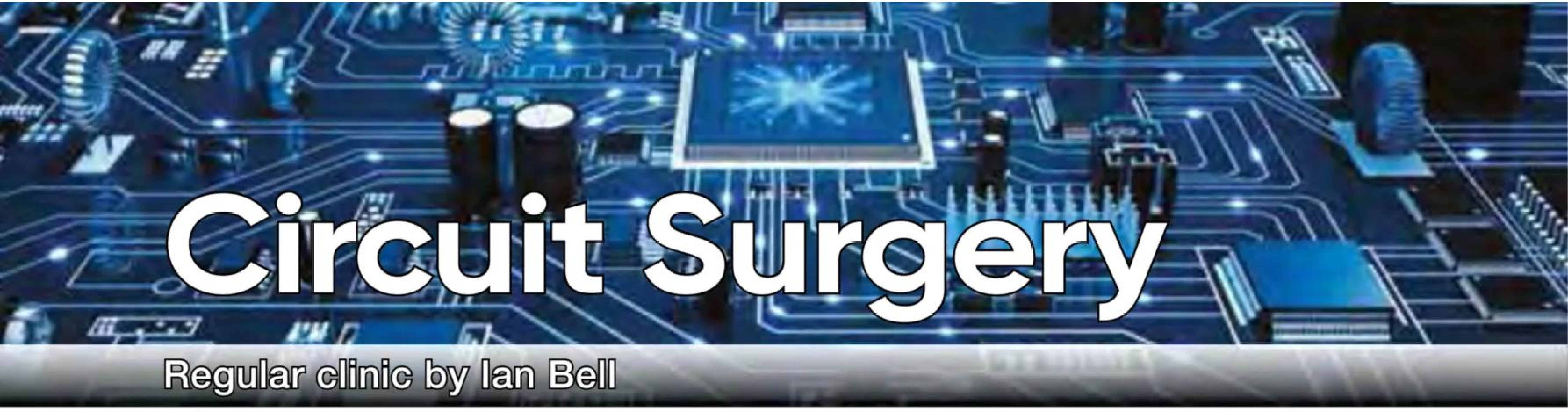


Circuit Surgery

Regular clinic by Ian Bell

Frequency shifting and superheterodyne receivers – Part 1

The topic for this month was suggested by *PE's* editor, Matt Pulzer – we will be looking at the principles behind superheterodyne radio receivers (often shortened to 'superhets'). Heterodyning is the process of shifting the frequency of a signal. This month, we will discuss the mixer circuits which are used to perform frequency shifting and next month we will look at radio systems in more detail.

The word heterodyne is from the widely used Greek root *hetero*, meaning 'other', and another ancient Greek root *dyne*, which is from *dunamis*, meaning 'power', although in the context of superhets it really means 'frequency'. The 'super' part of superheterodyne is short for 'supersonic', to indicate that use is made of frequencies beyond the audio range. Today, the term supersonic would usually refer to something moving faster than the speed of sound, such as a supersonic jet plane, and we would use the term ultrasonic for frequencies beyond the audio range.

Heterodyning

Heterodynes are frequency shifts used in a variety of electronic signal processing systems (not just in radio systems), for example, chopper-stabilised amplifiers for high-precision amplification of very-low-frequency signals. Heterodyning is often referred to as 'upshifting' / 'up conversion' or downshifting' / 'down conversion' (depending on the direction of frequency shift). Heterodyning occurs when signals of different frequencies are combined in a nonlinear way (more details on this later). Heterodyning is not restricted to electronic signal processing; in physics, heterodyning is used in a variety of measurement and detection techniques. For example, heterodyning of light waves in some types of microscopy and spectroscopy.

The term 'superheterodyne' was coined in 1918 by the inventor of the superheterodyne radio receiver, American electrical engineer Edwin Howard Armstrong. He developed and demonstrated the idea while serving in the US Army Signal Corps in France. However, the general principle of heterodyning predates this by almost 20 years and was invented by another pioneering radio engineer, Reginald Fessenden, working in the US, although he was born in Canada.

Despite being involved in various long-running patent disputes over various developments in radio technology, Armstrong was able to work with the Radio Corporation of America (RCA) on developing relatively easy-to-use and low-cost implementations of superheterodyne receivers. RCA produced the first commercial superheterodyne radios in the mid 1920s, and since the 1930s superheterodyne designs have dominated the commercial radio receiver market.

Radio fundamentals

Radio transmission systems are fundamentally based on heterodyning. The signal to be transmitted, referred to as the 'message signal' (for example, speech) is upshifted from its original frequency range (called the baseband) to the much higher frequencies (radio frequencies – RF) required for practical wireless transmission of electromagnetic signals. This is achieved by modulating (varying) properties (amplitude, frequency or phase) of a high frequency signal (the carrier wave) in sympathy with the message signal. Thus, we have the familiar and long-established AM (amplitude modulation) and FM (frequency modulation) and more modern techniques such as digital 64QAM and 256QAM (64 and 256-state quadrature amplitude modulation), which varies both phase and amplitude. QAM is used in systems such as Wi-Fi and 4G.

A radio receiver has to downshift the signal from the RF carrier frequency to the original baseband to recover the message. Recovering the original signal is referred to as 'demodulation' or 'detection'. For many radio receivers, such as domestic radios for speech and music AM and FM stations, there is a requirement to handle a wide range of carrier frequencies. Direct demodulation of wide-range RF signals makes the design of the demodulation circuits very challenging, potentially leading to high costs and/or implementations which require complex and skilled manual adjustments, not suited to use by the general public.

A key issue is that the performance of a demodulator circuit that is very good at a particular carrier frequency will degrade as the frequency moves away from this optimum value. The superheterodyne receiver solved this problem. The principle of the superheterodyne receiver is conversion (heterodyning) to a fixed intermediate frequency (IF) at which the demodulation is performed. This allows much of the radio's circuitry to operate at the fixed intermediate frequency, making it easier to design, providing good performance at relatively low cost, and not requiring adjustments by the user other than tuning into the desired station. The 'super' part of superheterodyne refers to the fact that the IF is much higher than the baseband frequencies (such as audio, hence 'supersonic', as noted earlier).

IF stages occur in many radio systems, including modern, largely digital, receivers where the IF signal(s) are fed to ADCs and then on to digital signal processing (DSP) for demodulation using custom integrated circuits (ICs) or FPGAs (field-programmable gate arrays). However, there are modern receivers that do not use IF and downconvert straight to the baseband. These systems, called direct-conversion receivers, are challenging to design due to a number of non-ideal behaviours, but with most of the circuitry implementable on an IC they have the potential for low cost, flexibility and low power consumption.

Mixers

A frequency mixer (or simply mixer) is a nonlinear circuit that combines signals at two frequencies to produce new frequencies (heterodynes). The

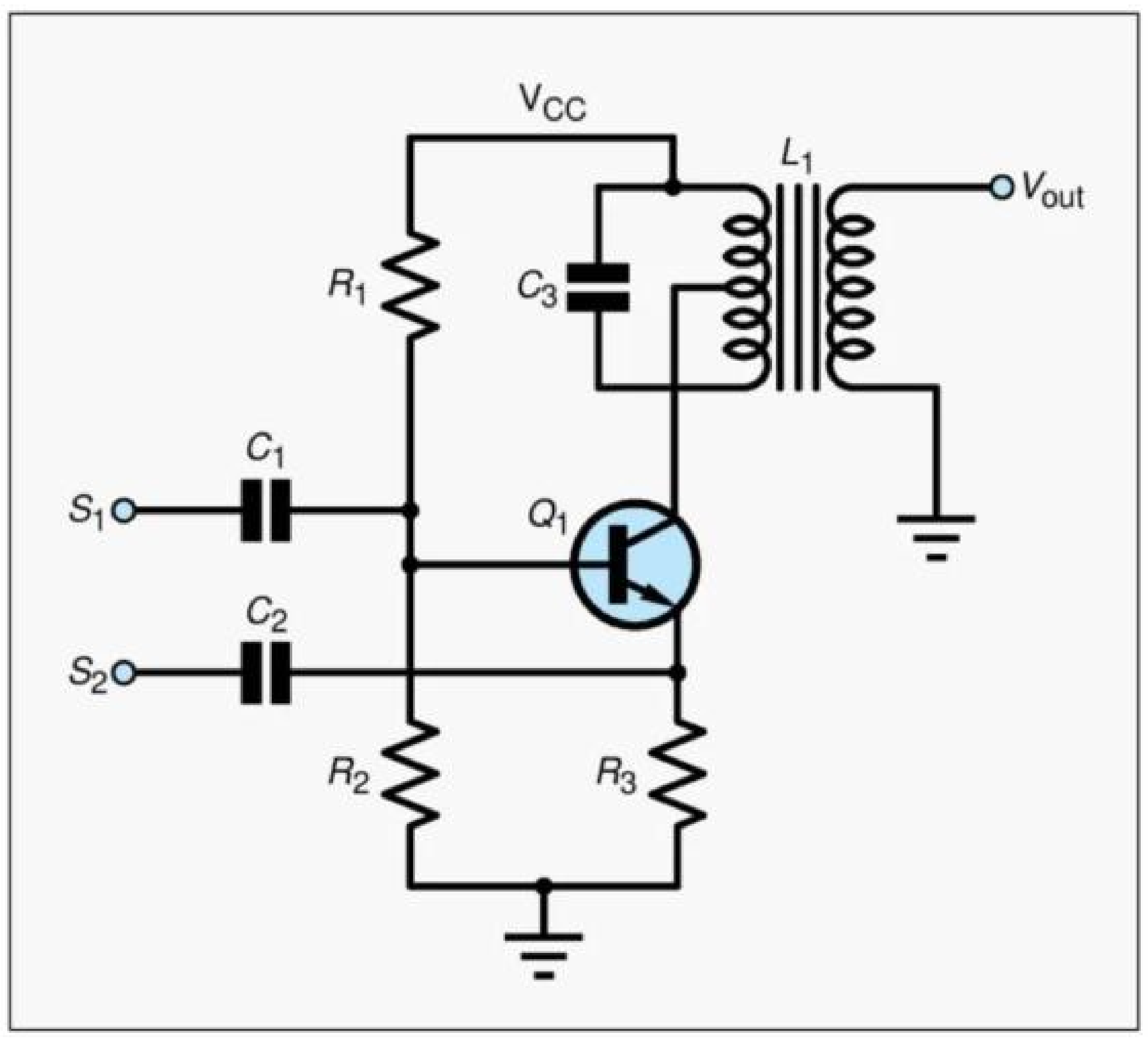
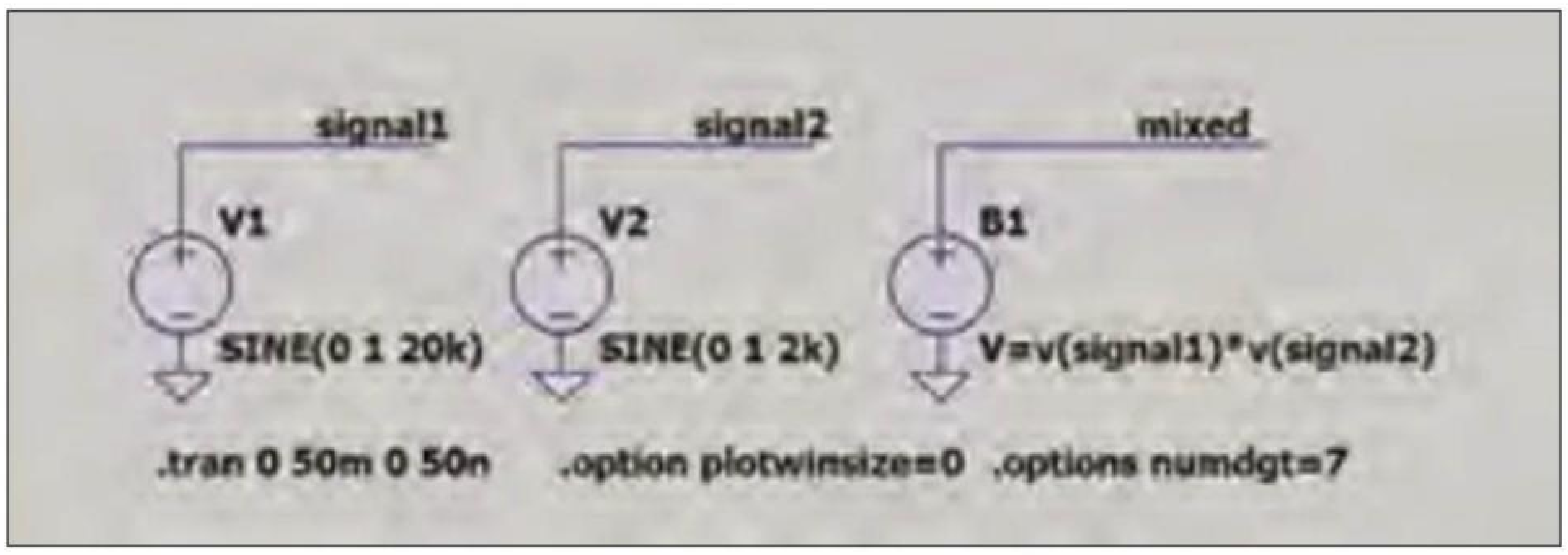


Fig.1. Basic single-transistor RF mixer circuit.



```
signal1          signal2          mixed
V1               V2               B1
SINE(0 1 20k)    SINE(0 1 2k)     V=v(signal1)*v(signal2)
.tran 0 50m 0 50n    .option plotwinsize=0  .options numdgt=7
```

Fig.3. LTspice schematic for behavioural simulation of multiplying mixer.

term 'mixer' can also be used when signals are scaled and added (this is a linear operation that does not produce new frequencies). A key example is an audio mixing desk. The meaning of the term should be clear from context.

An ideal mixer *multiplies* two signals. The circuitry in a basic radio receiver – particularly when built from discrete devices – is often not a direct implementation of the multiply function – typically the nonlinearity inherent in diodes and transistors is used (in the early days it was vacuum tubes/values). Fig.1 shows an example of a basic mixer based on a single bipolar transistor.

However, it is possible to build analogue circuits that multiply signals. In particular, the Gilbert multiplier circuit (also called the Gilbert cell), which was developed by Barrie Gilbert in the late 1960s, is often used. The core of the Gilbert cell uses six transistors, but more are required to implement the biasing (for example, a current source). This Gilbert multiplier is suited to integrated circuit implementations, where the high transistor count is not an issue, and it is common in IC-based radio circuits.

When considering the general principles of radio systems, we usually model mixers as multipliers and draw block diagrams of radio system architectures with mixers represented by the multiplier symbol, as shown in Fig.2.

The operation of a multiplying mixer can be explained mathematically by considering two sinusoidal signals (S_1 and S_2) as inputs to the mixer. We write these signals as:

$$S_1 = A_1 \cos(2\pi f_1 t)$$

and

$$S_2 = A_2 \cos(2\pi f_2 t)$$

Here, A_1 and A_2 are the signal amplitudes and f_1 and f_2 are their frequencies. The 2π factor converts the ordinary frequency of the signal (f) in hertz to an angular frequency (ω) measured in radians per second. Multiplying these two signals together gives:

$$S_1 S_2 = A_1 A_2 \cos(2\pi f_1 t)\cos(2\pi f_2 t)$$

To see the implications of this clearly in terms of different frequencies we need to convert the product of two cosines to individual sine or cosine functions. This problem was solved in in the sixteenth century by people interested in astronomy-based ship navigation. This led to the Prosthaphaeresis formulas, also known as Simpson's formulas – a set of four trigonometric identities, of which we need the following:

$$\cos\alpha\cos\beta = \frac{1}{2}\cos(\alpha-\beta) + \frac{1}{2}\cos(\alpha+\beta)$$

Applying this to the above signal expression gives:

$$S_1 S_2 = \frac{A_1 A_2}{2}\cos(2\pi(f_1 - f_2)t) + \frac{A_1 A_2}{2}\cos(2\pi(f_1 + f_2)t)$$

From this we can see that the mixed signal consists of two new sinusoids at the sum ($f_1 + f_2$) and difference ($f_1 - f_2$), of the input frequencies. Note that the input frequencies are *not* present in the output.

Multiplying mixer simulation

We can use LTspice to simulate idealised radio subsystems to help understand their principles of operation. A multiplying mixer can be implemented using a behavioural voltage source, as shown in Fig.3. Here we generate two sinusoids (`signal1` at 20kHz and `signal2` at 2kHz) using standard voltages sources (`V1` and `V2` respectively). These signals are multiplied together using the behavioural voltage source `B1` (with equation `V=v(signal1)*v(signal2)`). The frequencies are not representative of typical radio systems, but are convenient for displaying the results.

When considering the operation of radio systems, we are often more interested in the signal spectra (what frequencies are present) rather than the waveforms in the time domain.

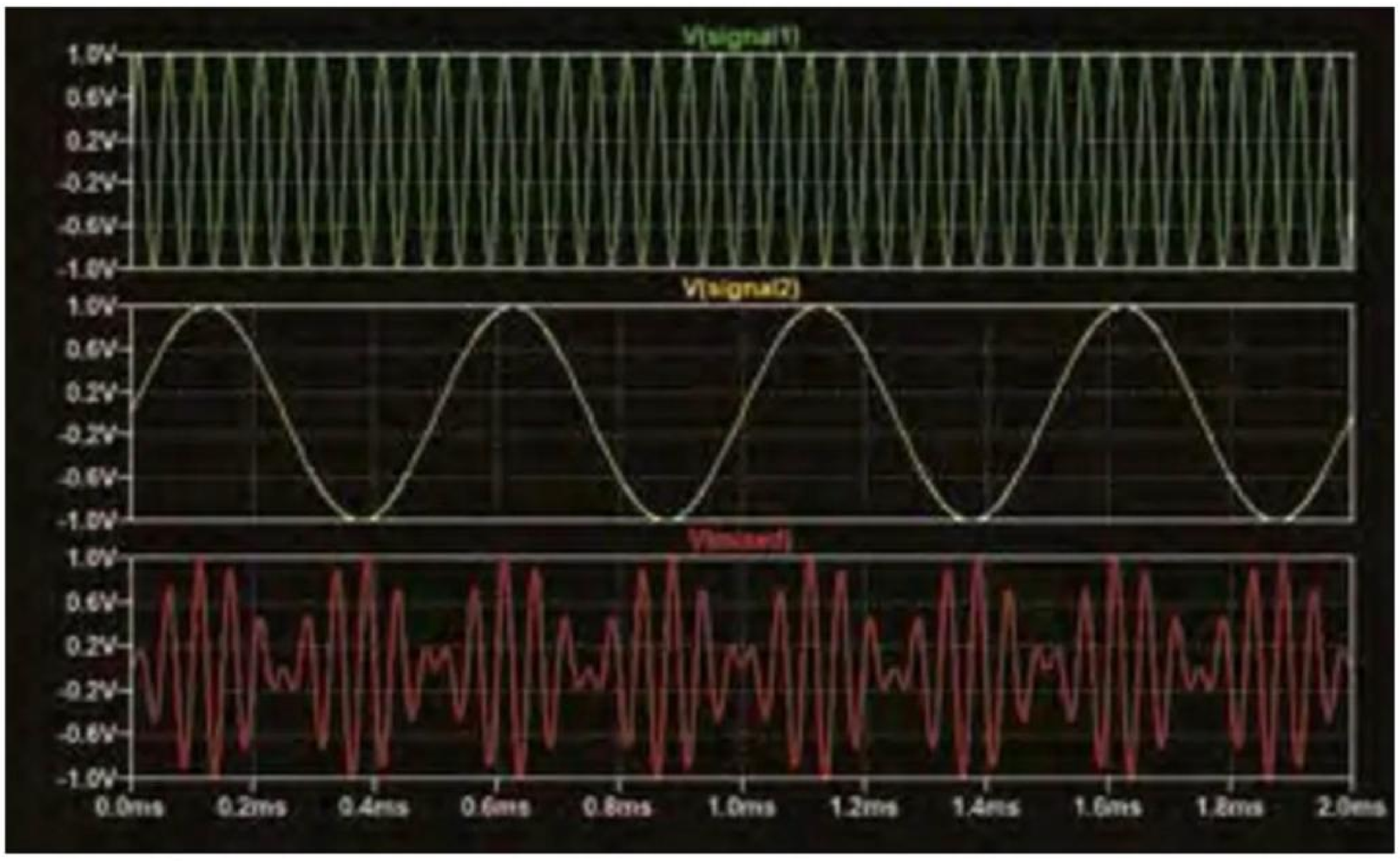


Fig.4. Waveform results from the circuit in Fig.3.

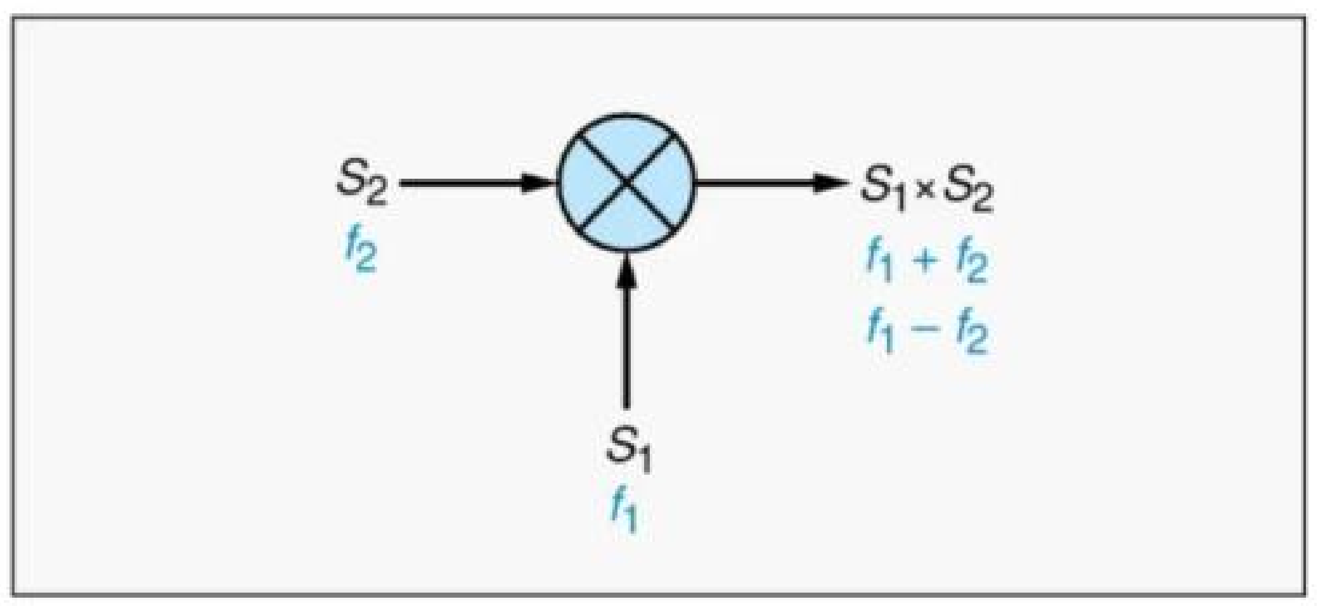


Fig.2. Multiplier/mixer symbol.

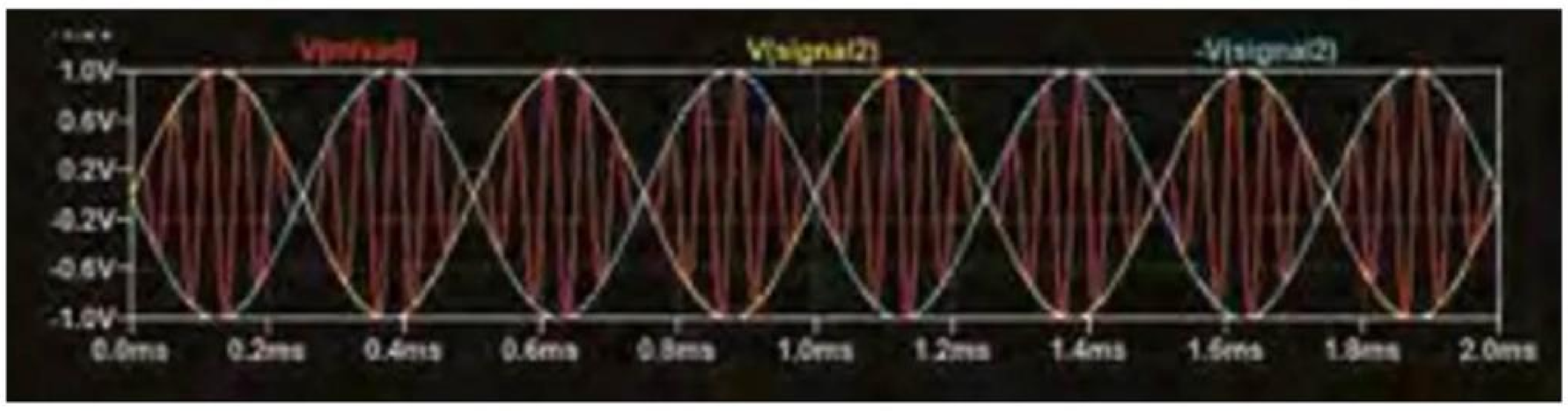


Fig.5. Waveform results from the circuit in Fig.3.

Therefore, the simulation is configured to facilitate viewing of the spectrum with LTspice's FFT (Fast Fourier Transform) function. This requires a relatively long simulation with a relatively small timestep in comparison with what is required just to view the waveforms. We also use the directives to prevent LTspice from compressing the waveform data (`.option plotwinsize=0`) and use double-precision math (`.options numdgt=7`) to improve FFT accuracy.

The waveforms from the simulation in Fig.3 are shown in Fig.4. We see that the mixed waveform looks like the amplitude of the higher frequency signal is being varied by the low frequency signal. Indeed, this is the case – an amplitude modulated (AM) radio signal can be produced by a multiplying mixer. Fig.5 shows the low-frequency waveform (`signal2`) and its inverse (`–signal2`) match the amplitude envelope of the mixer output. Although the setup for AM is not exactly as shown in figure, in radio terms `signal1` in Fig.4 can be thought of as acting like a carrier wave and `signal2` represents the message.

The spectra of the signals in Fig.4 are shown in Fig.6. These are obtained in LTspice by right-clicking the waveform of interest and selecting **View > FFT**. The default configuration for the FFT was used here. The initial display shows a lot of detail at lower amplitudes, but the minimum dB axis value was changed to –100 dB to simplify the plots. The two input signals have a single peak at their respective frequencies of 20kHz and 2kHz, as expected for ideal sinewaves. The sub –100 dB amplitudes at other frequencies (less the 1/10000 of the peak value) are due to the fact that the FFT calculations are not perfectly accurate because of practical limits on the number of data points and the numerical precision of the simulation and FFT.

The spectrum of the mixed signal in Fig.6 has two peaks at 18kHz and 22kHz. These are at the sum (20kHz + 2kHz = 22kHz) and difference (20kHz – 2kHz = 18kHz) frequencies. This is as expected from the formula obtained above. The output spectrum of the mixer does not contain the two input frequencies, just their sum and difference. Again, this follows from the equations above.

Beats and heterodynes

Heterodyne (mixer) circuits are sometimes referred to using the term 'beat'; for example, a 'beat frequency oscillator' used as an input to a mixer in a radio receiver. However, this could be confusing because the term 'beat' or 'beat frequency' in acoustics refers to the interference pattern which occurs between tones at two slightly different frequencies. Interference is the addition of the two waves at each point in space, so it is a linear process. Similar interference patterns can occur in other physics domains, such as with light waves (see Thomas Young's famous double-slit experiment).

Unlike multiplying, adding two sinusoidal signals does not produce any new frequencies in the spectrum of the output signal, but the amplitude of the combined signal varies at a rate proportional to the difference in the two frequencies. In acoustics, if we produce two pure tones (sinusoidal) the human listener may perceive this amplitude variation as either a pulsing in volume or a separate audible tone, depending on the frequency of amplitude variation in relation to the human hearing range and the degree of separation of the tones.

Fig.7 shows an LTspice simulation set up in a similar way to that in Fig.3. The key difference is that the behaviour source (`B1`) is adding rather than multiplying the signals (`signal1` and `signal2`). The resulting signal is labelled `beat` in reference to the audio beat frequencies just discussed. The signals being added are at 18kHz and 22kHz (the same as the output frequencies in the previous example). The waveforms are shown in Fig.8. The waveform shape of the output (`beat` signal) is the same as the output from the multiplier in Fig.7 – this is to be expected as the same two frequencies are present at equal amplitudes in both cases.

The spectra in Fig.9 show the key difference between the additive and multiplicative circuits. For the circuit in Fig.7 the frequencies in the output (`beat` signal) are the same as the frequencies in the input (`signal1` and `signal2`). Unlike for the multiplying mixer, none of the signals match the envelope of the output waveform. This is a sinewave at a frequency which is half the difference between frequencies of the added sinusoids (since

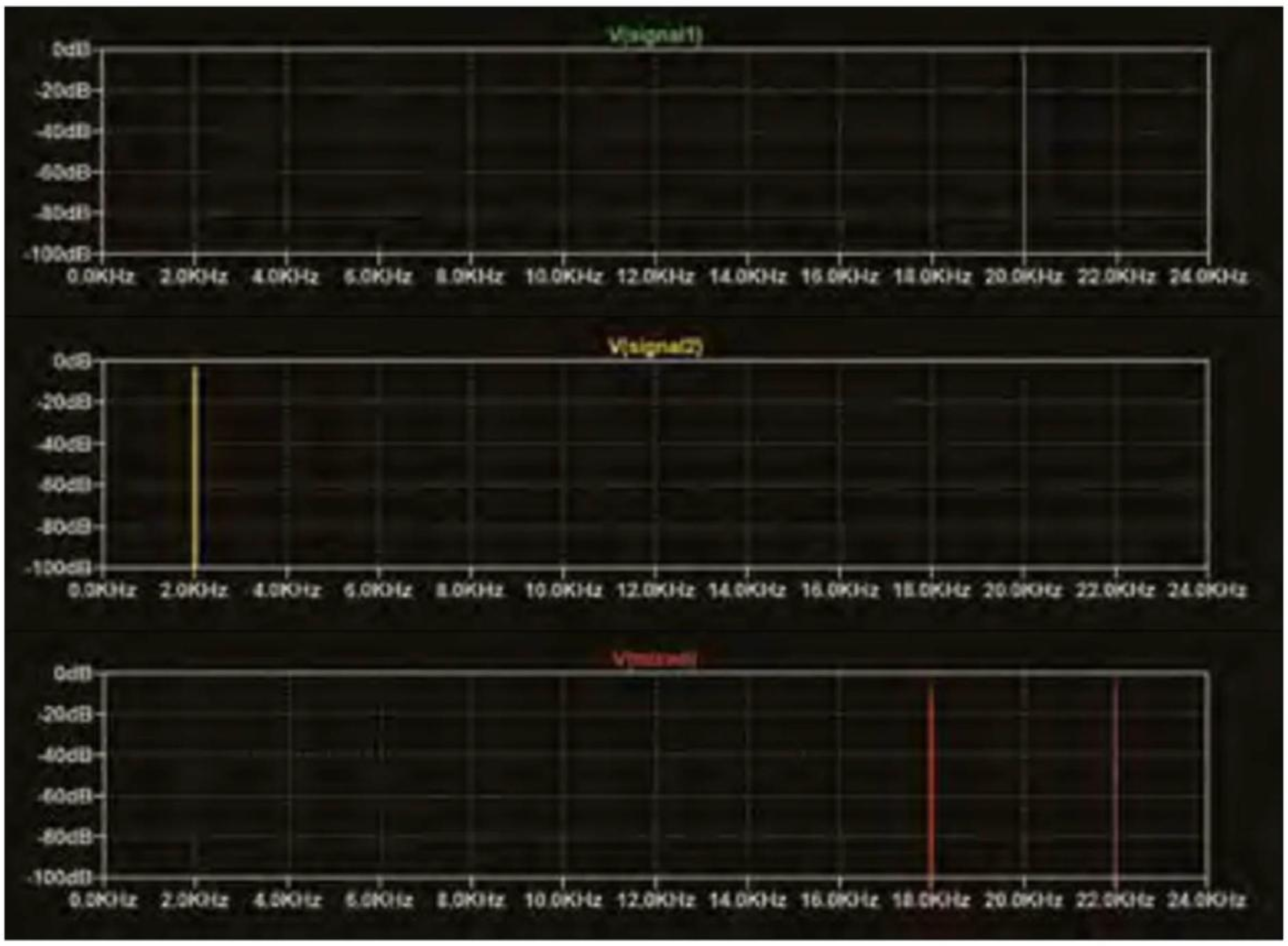
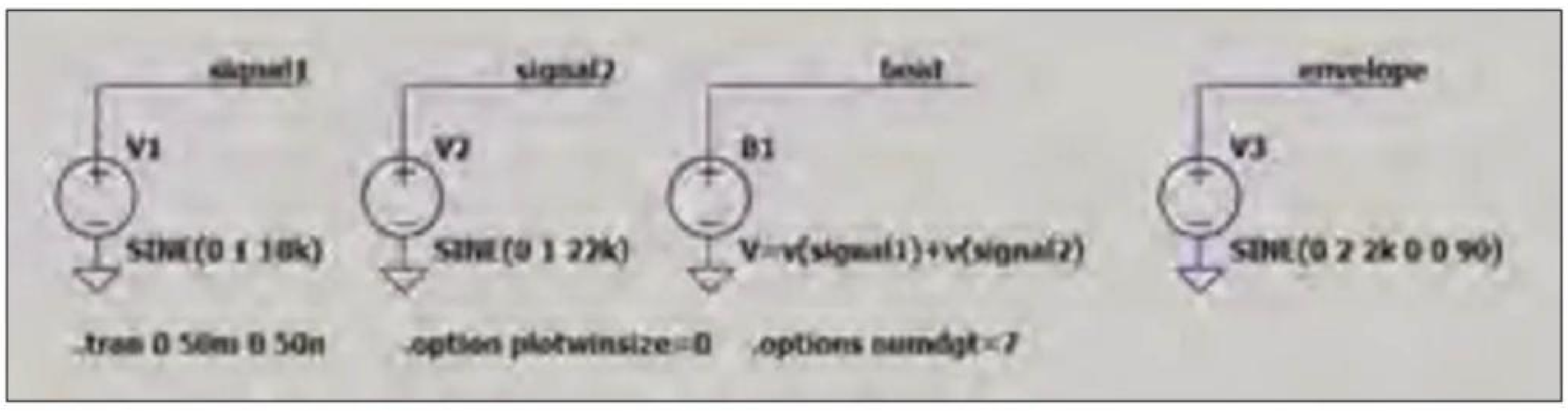


Fig.6. Spectra of signals from the waveforms in Fig.4.



```
.tran 0 50m 0 50n
.option plotwinsize=0
.options numdgt=7
```

Fig.7. LTspice schematic for behavioural simulation of signal addition.

(22 – 18)/2 = 2 in kHz). In Fig.7 there is an additional sinusoidal voltage source (V3) which produces a signal that matches the amplitude envelope (see Fig.10).

Nonlinear mixers

As noted above, not all mixer circuits are multiplier implementations, particularly those in basic or early radios and those using discrete components. If we apply the sum of two signals to any circuit with a nonlinear response heterodyning will occur. Looking at Fig.1 we see that the voltage across the base-emitter junction of the transistor is the difference between the two input signals. This is effectively the sum of the signals (with a sign change). The voltage-current relationship of the junction is nonlinear (thanks to the exponential diode voltage-current relationship), so the base and hence collector current will contain additional frequencies (heterodyning).

We can show the general behaviour of a nonlinear circuit mathematically by assuming the relationship between input and output is a polynomial. Mathematical theory shows that many functions can be approximated by polynomials – you may have used a 'polynomial fit' to draw a line through data on a graph. A polynomial of a variable *x* is the weighted sum of its powers (*x*, *x*-squared, *x*-cubed and so on, where each power of *x* is multiplied by a fixed value (coefficient) *k*). We can write this as:

$$k_0 + k_1 x + k_2 x^2 + k_3 x^3 + k x^4 \ldots$$

If *x* is the input to our nonlinear circuit and it happens to be the sum of two sinusoids ($S_1 + S_2$), where:

$$S_1 = A_1 \cos(2\pi f_1 t)$$

And

$$S_2 = A_2 \cos(2\pi f_2 t)$$

as previously discussed for the multiplier, then, if we just consider the k_2x^2 term, we have:

$$k_2 x^2 = k_2 (A_1 \cos(2\pi f_1 t) + A_2 \cos(2\pi f_1 t))^2$$

Multiplying out the squared terms we get:

$$k_2 x^2 = k_2 (A_1^2 \cos^2(2\pi f_1 t) + A_1 A_2 \cos(2\pi f_1 t)\cos(2\pi f_2 t) + A_2^2 \cos(2\pi f_2 t))$$

The A_1A_2 term in the middle is equivalent to the output for the multiplier discussed above – so this will produce the sum and difference frequencies: ($f_1 + f_2$) and ($f_1 - f_2$). The cos² terms imply multiplying two signals of the same frequency – again we get the sum ($f + f = 2f$) and difference ($f - f = 0$), so the output will also contain frequencies of twice the two input frequencies and some DC (zero frequency).

The k_1x polynomial term will add the original input frequencies to the output and

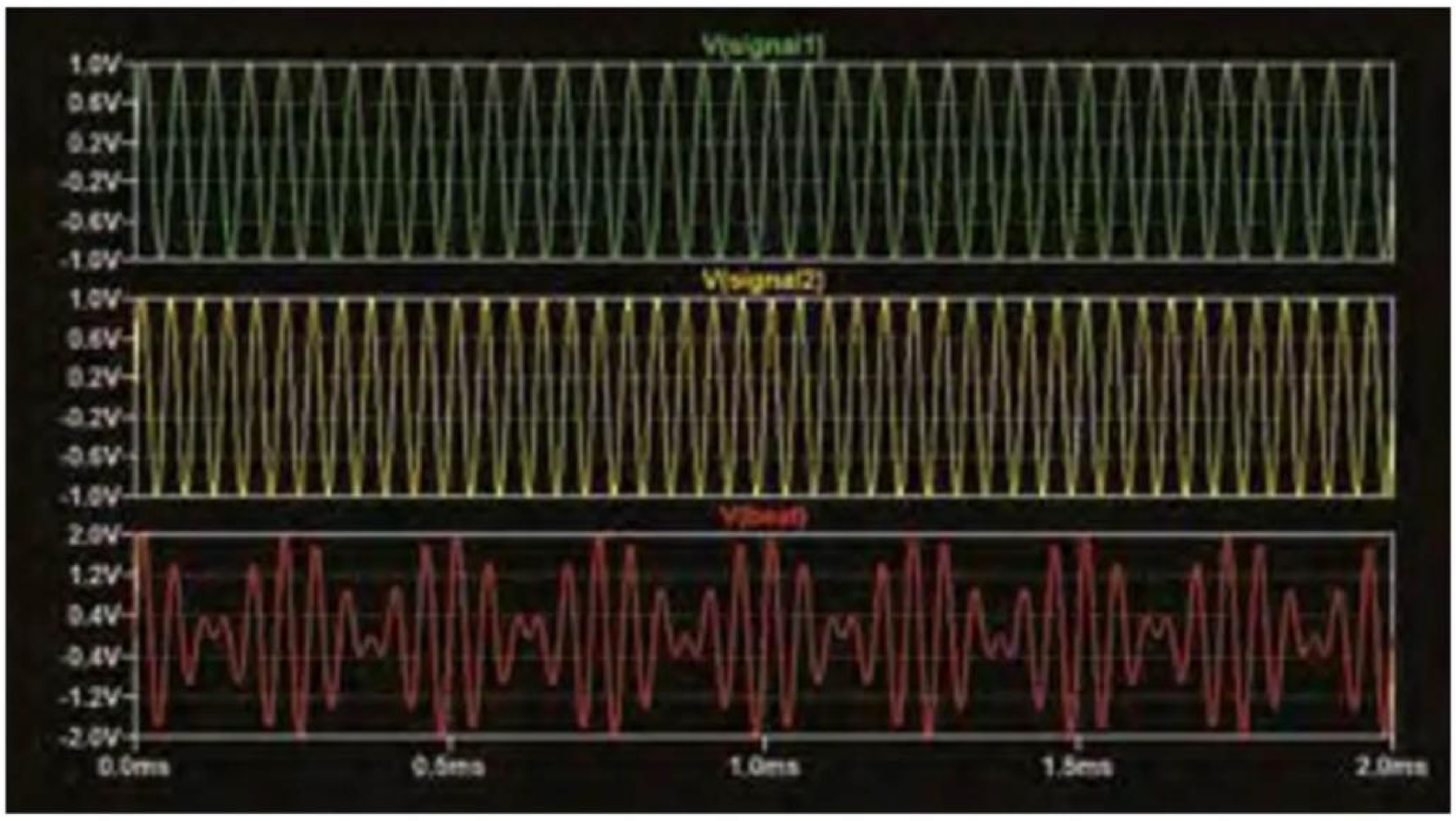


Fig.8. Waveform results from the circuit in Fig.3.

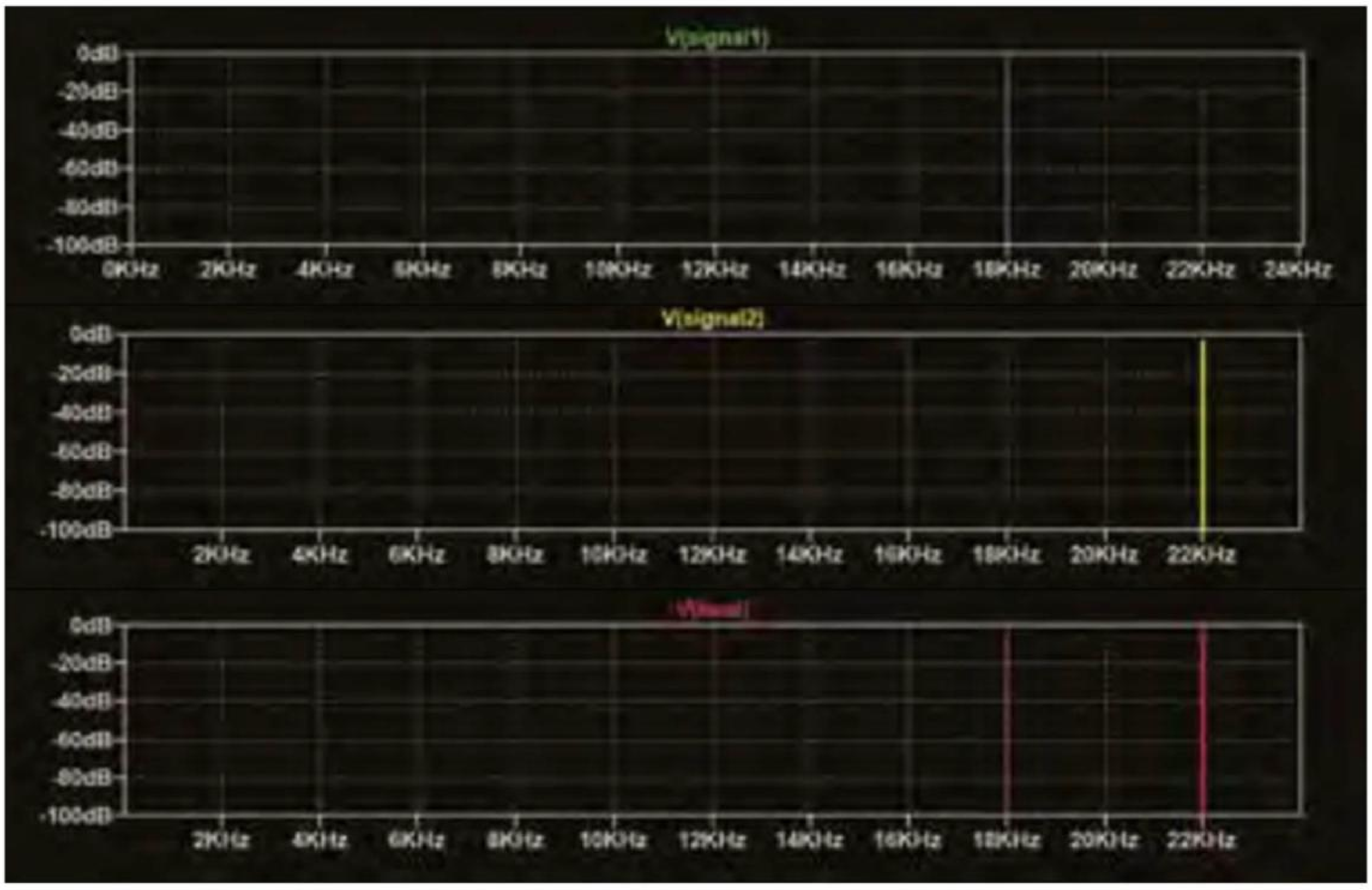


Fig.9. Spectra of signals from the circuit in Fig.7. Note that there are no new frequencies in the output (beat signal).

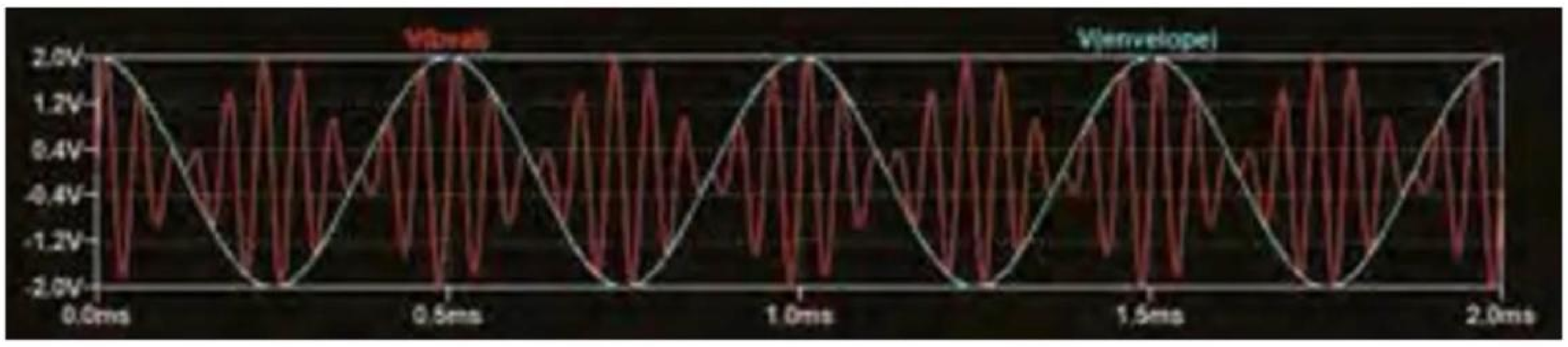


Fig.10. Envelope of beat signal from Fig.8.

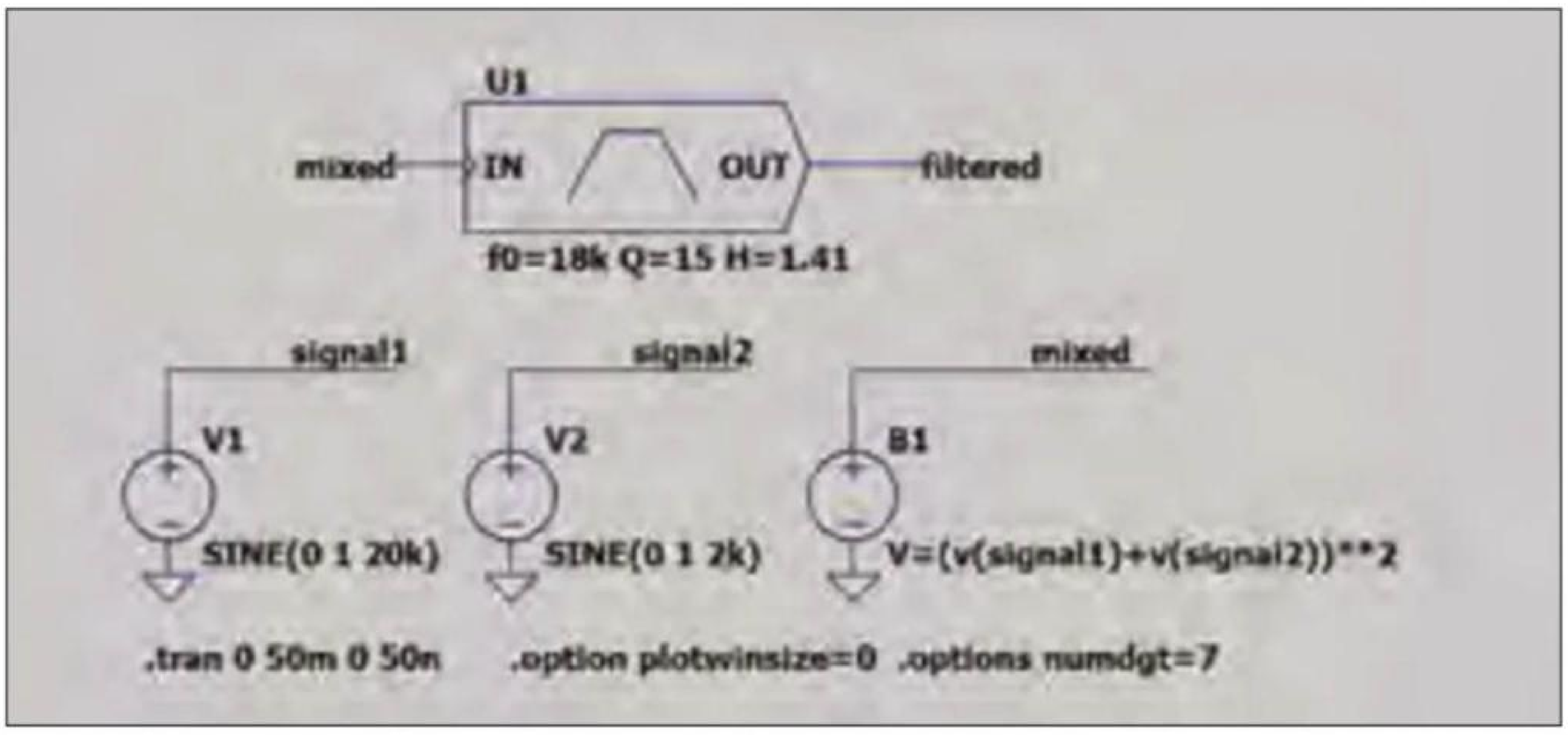


Fig.11. LTspice schematic for behavioural simulation of nonlinear mixer using squaring.

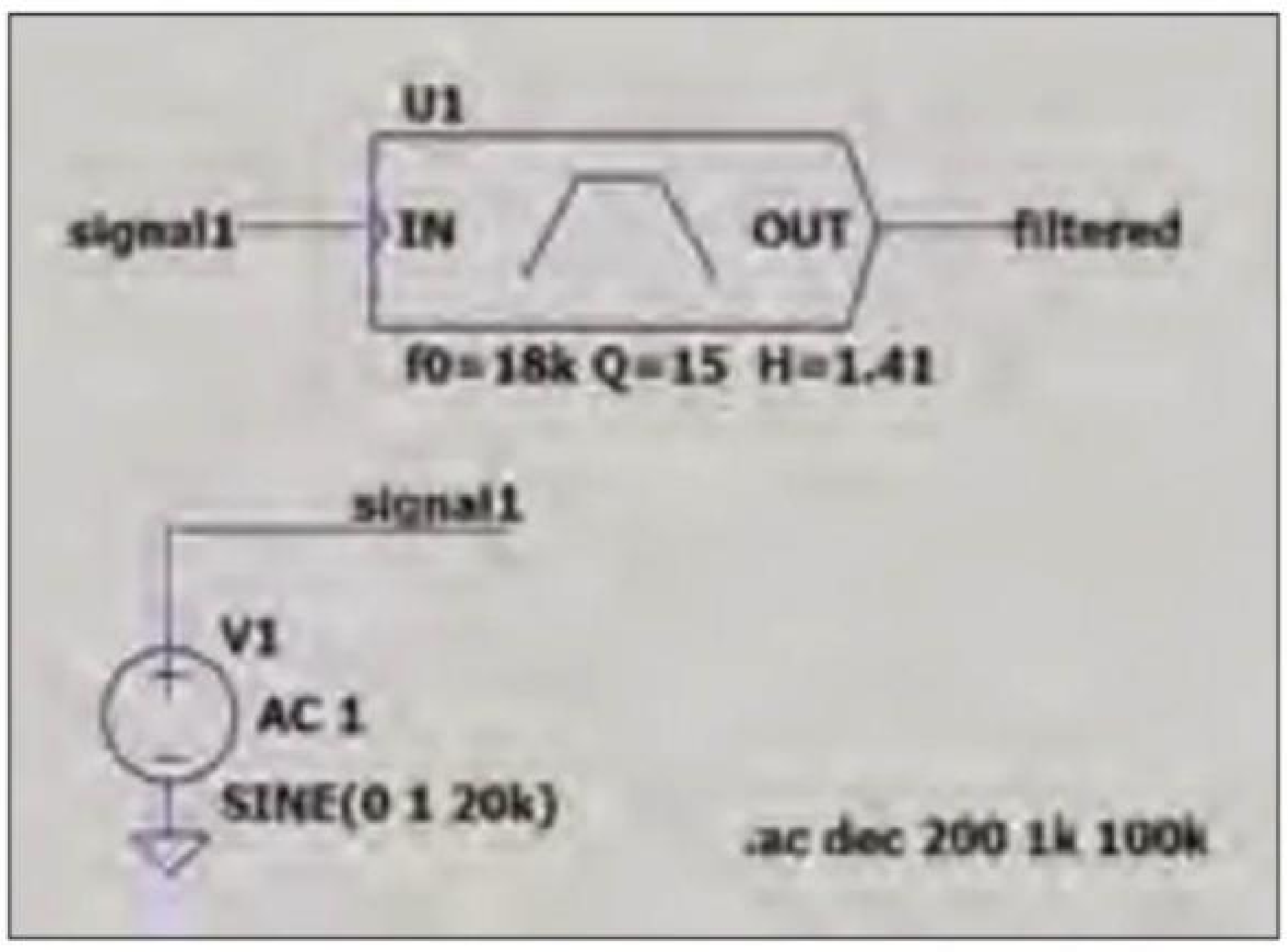


Fig.12. LTspice schematic for obtaining the frequency response of the filter in Fig.11.

the k_0 indicates the possibility of DC in the output. The higher-order terms produce many other frequencies, including at integer multiples of the two input frequencies and various additive combinations of these.

The fact that a nonlinear mixer produces a wide range of output frequencies means that we usually need a filter circuit on the output to remove the unwanted frequencies. Even with the multiplier mixer we may only want one of the outputs (either the sum or difference frequencies), so a filter may be needed here too. In the mixer circuit in Fig.1, the *LC* circuit (L_1 and C_3) implements the filtering of the output signal. The *LC* circuits passes a narrow range of frequencies around it's resonant frequency to the next stage via the transformer secondary.

Nonlinear mixer simulation

Fig.11 shows another simulation schematic similar to the previous examples. This is a mixer configured to produce the square of the sum of two input sinusoids – `signal1` at 20kHz and `signal2` at 2kHz – the same inputs as in Fig.3. From the mathematics discussed above we expect the circuit to produce four frequencies $f_1 - f_2$ (18kHz), $f_1 + f_2$ (22kHz), $2f_1$ (40kHz) and $2f_2$ (4kHz), plus some DC.

The schematic also includes a bandpass filter (`U1`) to attenuate unwanted frequencies. The 'wanted' signal here is selected to be the 18kHz ($f_1 - f_2$) output. The filter is implemented using the LTspice behavioural second-order bandpass filter, which is available in the `SpecialFunctions` folder of the component selector with name `2ndOrderBandpass`. The filter is for illustrative purposes only – it was not set up to meet any specific requirements. The LTspice schematic in Fig.12 can be used to plot the frequency response of the filter.

The output waveforms for the circuit in Fig.11 are shown in Fig.13. Despite having the same inputs as the circuit in Fig.3 the mixer output waveform has a significantly different shape due to the additional frequencies present. It also has a DC offset, as predicted above. The filtered waveform is closer to a pure 18kHz sinewave in shape, but not perfectly so as the filter does not complexly remove the other frequencies.

The spectrum of the mixed signal is shown in the top trace in Fig.14. The four frequencies mentioned above can be seen. The spectra in this figure were obtained using the Blackman windowing function in the LTspice FFT configuration. This is because the full waveforms are not necessarily integer number of cycles of repeating wave shape. Windowing functions 'fade out' the ends of the waveform to avoid abrupt signal changes or other differences at the ends from causing errors in the FFT.

This nonlinear mixer has a relatively simple behaviour (just a squaring function) but produces a more complex output than the ideal multiplier mixer discussed earlier. It is often the case that we need to remove some of the output from a mixer using a filter. The middle trace shows the filter frequency response used in this example. This is an 18kHz bandpass filter, which reduces the amplitude of frequencies away from 18kHz. This can be seen in the lower spectrum, which is for the filter output. The attenuation of the unwanted signals is not perfect here, but the filter was not set up to provide a specific performance. In general, unwanted mixer output frequencies may be close to wanted frequencies, which leads to demanding filter specifications.

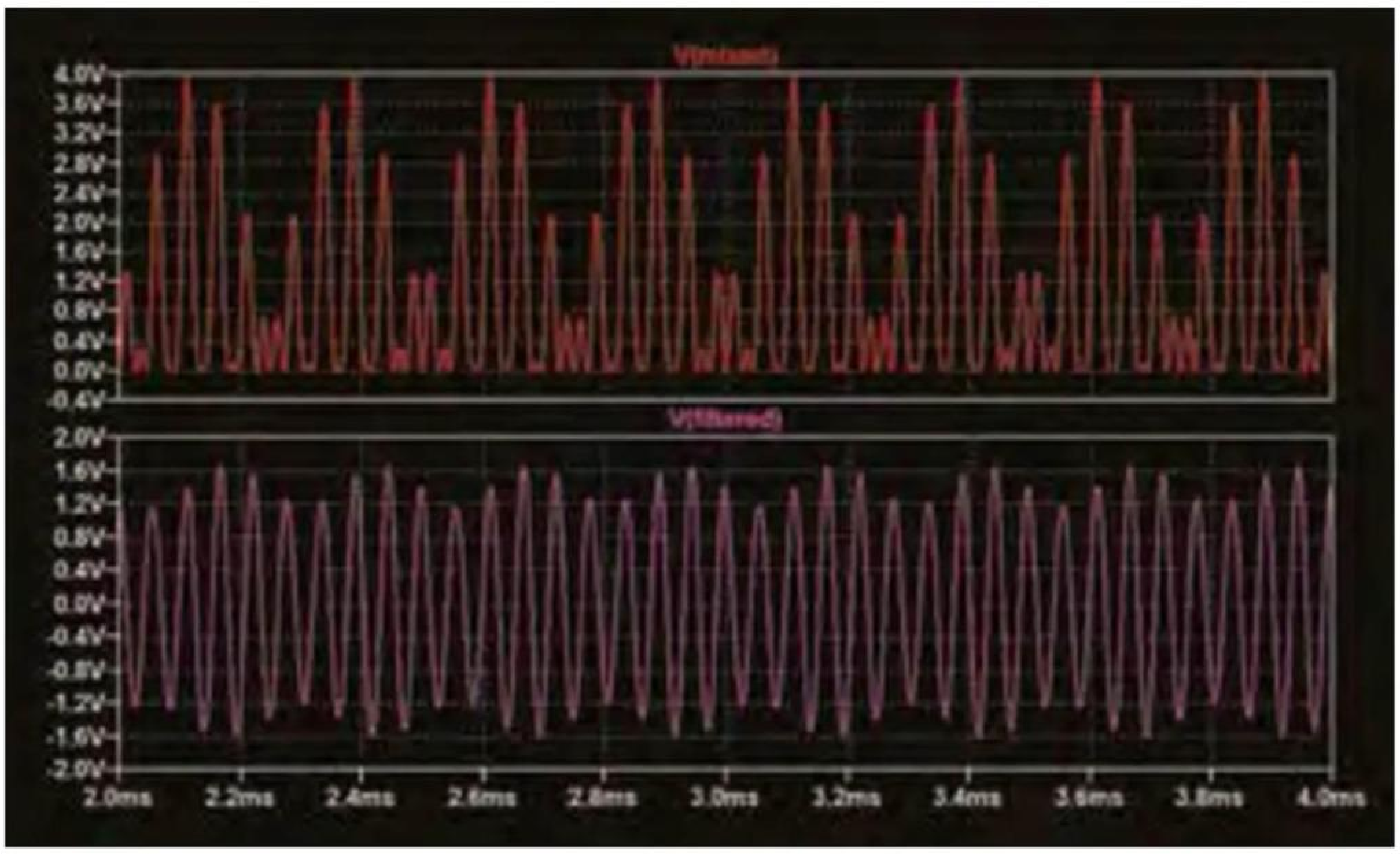


Fig.13. Waveform results from the circuit in Fig.11. Input signals are the same as in Fig.4.

Introduction to LTspice

Want to learn the basics of LTspice? Ian Bell wrote an excellent series of *Circuit Surgery* articles to get you up and running, see *PE* October 2018 to January 2019, and July/August 2020. All issues are available in print and PDF from the *PE* website: **https://bit.ly/pe-backissues**

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*. The examples and files are available for download from the *PE* website: https://bit.ly/pe-downloads

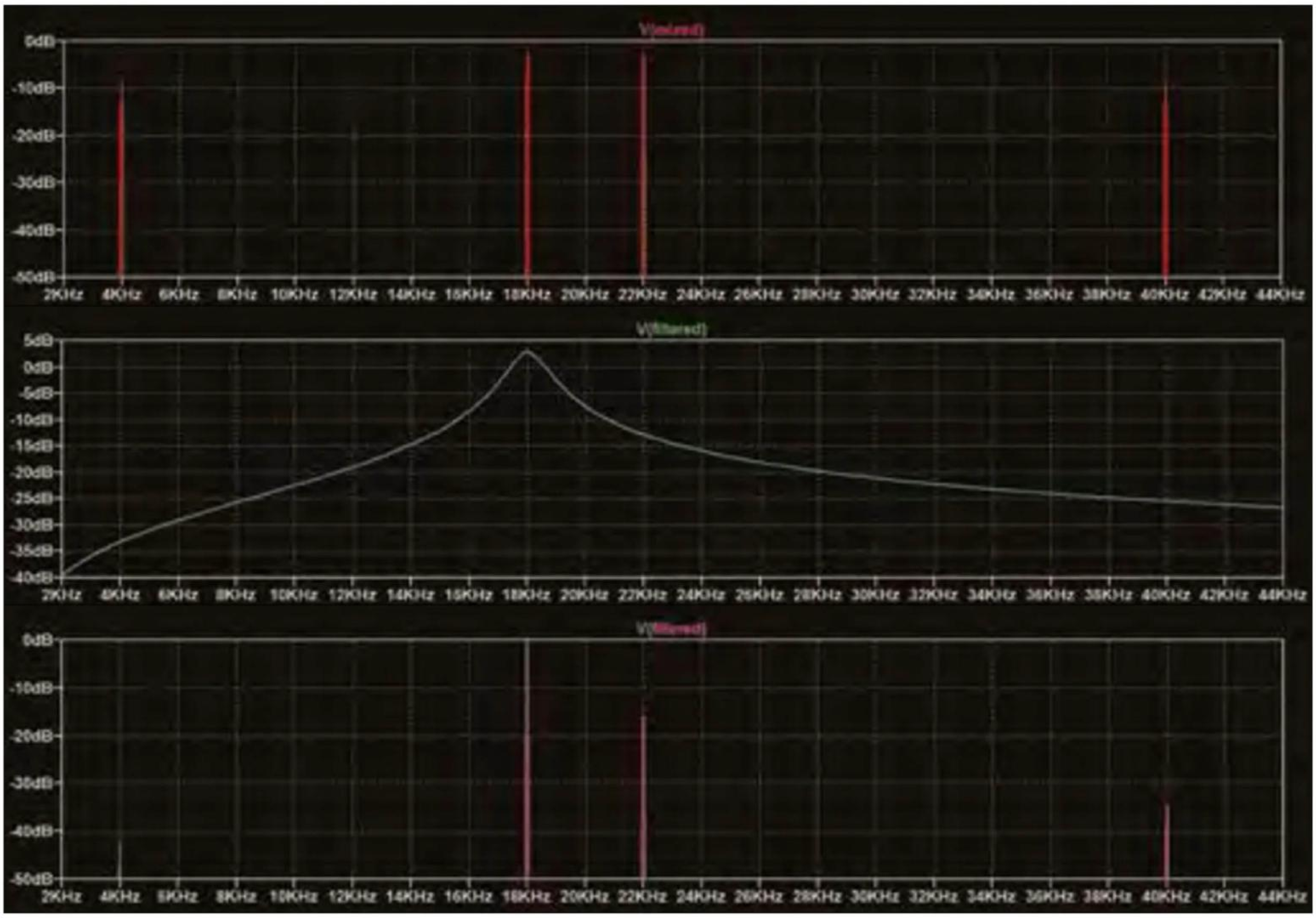


Fig.14. Spectra of signals in Fig.13 together with frequency response of the bandpass filter.

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MITCHELECTRONICS

Learn the basics of electronics with Robin Mitchell

The 555 Timer IC – Part 1

MitchElectronics is a series of projects by Robin Mitchell that introduces beginners to useful, simple, easy-to-understand circuit designs. Each month, he will introduce fundamental components, theory and ideas used in electronics. The series will cover both analogue and digital electronics.

Modern electronics has changed our world, providing us with all kinds of advanced technology, from smartphones and tablets to supercomputers, and even intelligent toasters that can be remotely operated from anywhere on the planet. Now, while such advances have been massively beneficial, it can also make electronics seem like a complex subject that only a few can understand. Worse, many modern projects that introduce makers to electronics often use complicated devices such as microcontrollers which use a 'black box' approach, meaning that the inner workings are hidden and not properly explained.

However, when electronics was still young (pre-1970s), many would build their own circuits consisting of a handful of parts that could be easily understood. Even if the circuits used complex or sophisticated analogue theory, such as Wien bridge oscillators or advanced filters, they could still be built on stripboard, using discrete through-hole parts and wires.

Recognising the challenges faced with modern electronic projects, MitchElectronics has developed a range of kits that only use simple components to build all kinds of projects, such as light flashers, oscillators, musical instruments, and even functional equipment. In this *Practical Electronics* series, we will cover a whole range of fundamental circuits that have played a critical role in the field of electronics, learning how they work, and how to build them.

Project introduction

In this article, we will cover the well-known 555 timer IC, and show how it can be used to create two useful circuits: a 555-based astable and a monostable. These two circuits are fundamental to many electronic designs.

What makes these circuits great for beginners is that they use just one chip, and they can easily be used with other circuits for timing purposes. An astable provides a constant series of voltage pulses (think of a pendulum), switching between a high and low voltage, while the monostable provides a single pulse for a pre-set amount of time, just like turning a tap on and off.

Fig.1. MitchElectronics 555 Astable and 555 Monostable Kit bags, ready to be built.

By reading this article, you will learn how to build these circuits, how to design your own timers, how to calculate LED currents, and the importance of various components in electronic circuits.

Both the circuit kits (Fig.1) discussed in this article can be purchased from MitchElectronics, and if you want to see this project in action, then you should definitely check out the *MitchElectronics Practical Electronics Video Series* (coming out December 2023), just visit: **www.mitchelectronics.co.uk**

How the parts work

Before we jump into the astable and monostable circuits, we first need to learn about a few basic components, including what they do, and why they are important.

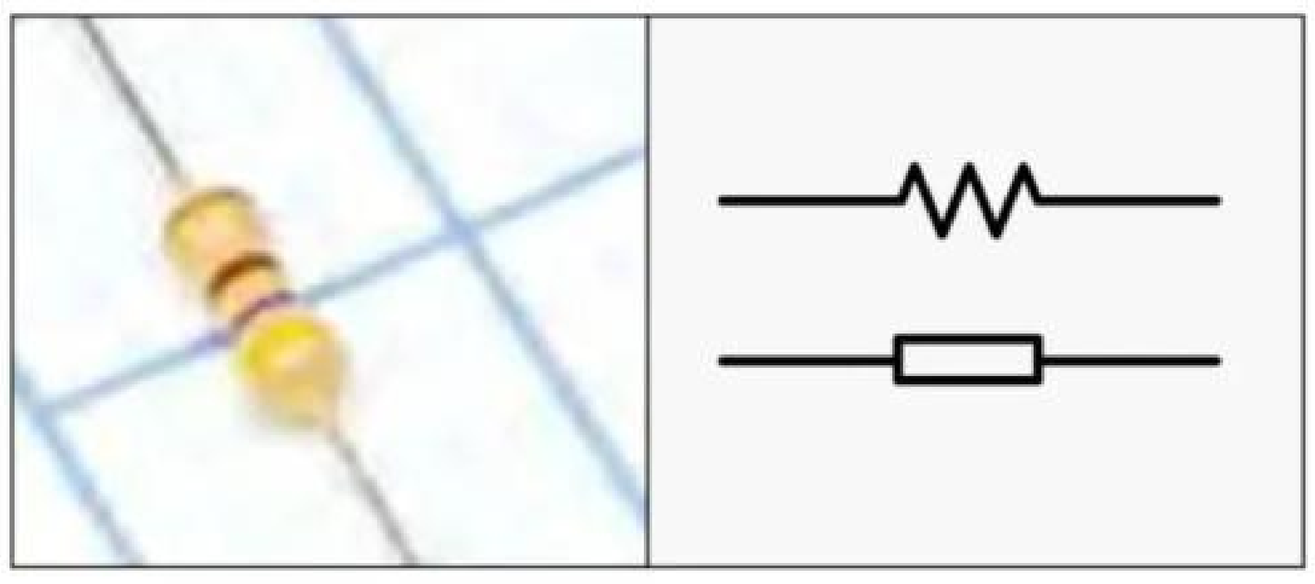


Fig.2. Carbon film resistor (left) and resistor circuit symbols (right). The box and 'sawtooth' versions are both widely used – *PE* uses the latter.

What are resistors?

Resistors are one of the most common and basic electronic components. Their symbol and an example of a resistor are shown in Fig.2. As their name suggests, they 'resist' electrical current. Resistance is measured in ohms, indicated with the Greek upper-case symbol for omega (Ω), but because the ohm unit is quite a small value, resistors in electronics typically have resistances between 100 and 100,000 ohms. We would normally write this as '100Ω' and '100,000Ω', although the latter is usually shown as 100kΩ, where the 'k' (always lower case) means 1000 – kΩ is pronounced 'kilohms'.

The current flowing through a resistor is proportional to the voltage across it, meaning that as the voltage across a resistor is increased, the current also increases proportionally. This is known as Ohm's law, first proposed by German physicist Georg Ohm, after whom the resistance unit is named. The formula that relates the current to the voltage is given as:

$$I = \frac{V}{R}$$

For example, if a voltage of 1V (volt, symbol V, is the unit of electrical potential or voltage) is applied across a resistor with a resistance of 10Ω, the resulting current flowing through that resistor will be 0.1A (amp, symbol A, is the unit of electrical current):

$$I = \frac{V}{R} = \frac{1V}{10\Omega} = 0.1A$$

Resistors can be made from all kinds of materials, but the ones used in the MitchElectronics kits are made from carbon film (specifically, quarter-watt carbon-film axial resistors). Because these resistors are small and round, it's difficult to print the resistor value across the body. Instead, manufacturers use colour bands to indicate their value. To learn more about this, visit: **https://bit.ly/mitch-res**

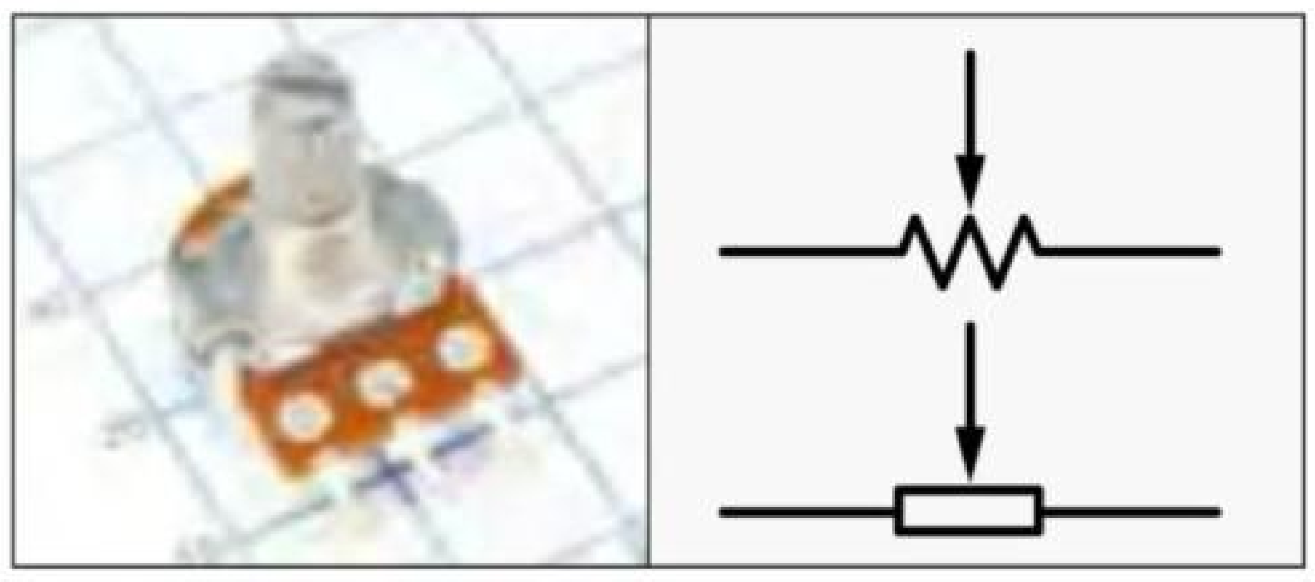


Fig.3. Potentiometer schematic symbol. The box and 'sawtooth' versions are both widely used – *PE* uses the latter.

What are potentiometers?

Potentiometers, often just called 'pots', are three-pin devices that can be used to produce a *variable* resistance, which is then used to produce a variable voltage or current. They almost always have a moveable mechanical component (such as a knob) that allows their setting to be altered. Potentiometers are commonly found on amplifier volume controls, and are also found on many other kinds of electronic equipment that need some kind of value varied, for example, measurement test gear and musical equipment. The symbol for a potentiometer is shown in Fig.3.

Potentiometers used in MitchElectronics kits have three connection pins, and inside the potentiometer is a carbon track between the two outer pins with the third pin connected to a wiper that makes sliding contact with the carbon track. The resistance between the two outer pins will always be the same, but the resistance between one of these outer pins and the inner pin will depend on where the knob is positioned, and which outer pin is being measured. Fig.4 shows the type of potentiometer you will use in these projects.

If one of the outer pins is connected to a positive supply, and the other to ground, the middle pin will produce a voltage whose value depends on the knobs position. Turning the knob towards the positive supply will increase the output voltage, while turning the knob towards ground will decrease the output voltage.

What are capacitors?

Capacitors are two-pin electronic components that can store electric charge, making them similar to batteries – but, unlike batteries, which can store massive amounts of energy and power circuits, capacitors are used to provide relatively small amounts of power for small amounts of time. This can be used to for timing purposes, smoothing power lines, and filtering signals. Several different symbols for capacitors are shown in Fig.5, and some examples of actual devices are shown in Fig.6. Unlike resistors, which tend to be pretty uniform in shape, capacitors come in all sorts of shapes, sizes and colours.

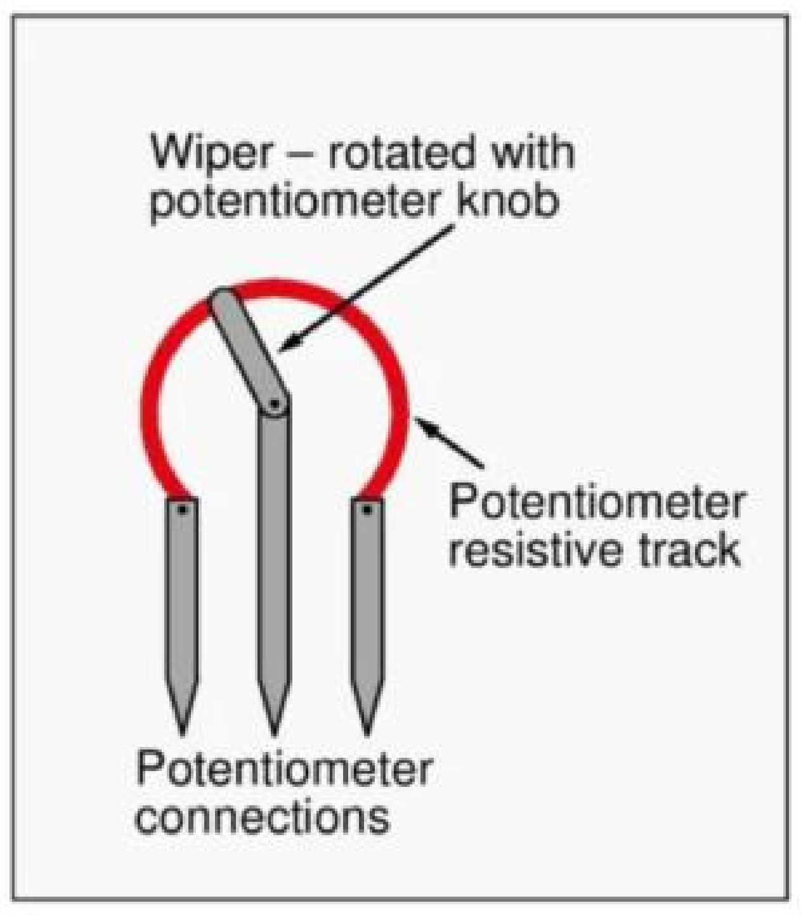

Wiper – rotated with potentiometer knob
Potentiometer resistive track
Potentiometer connections

Fig.4. Potentiometer constructon showing resistive track, wiper and terminals.

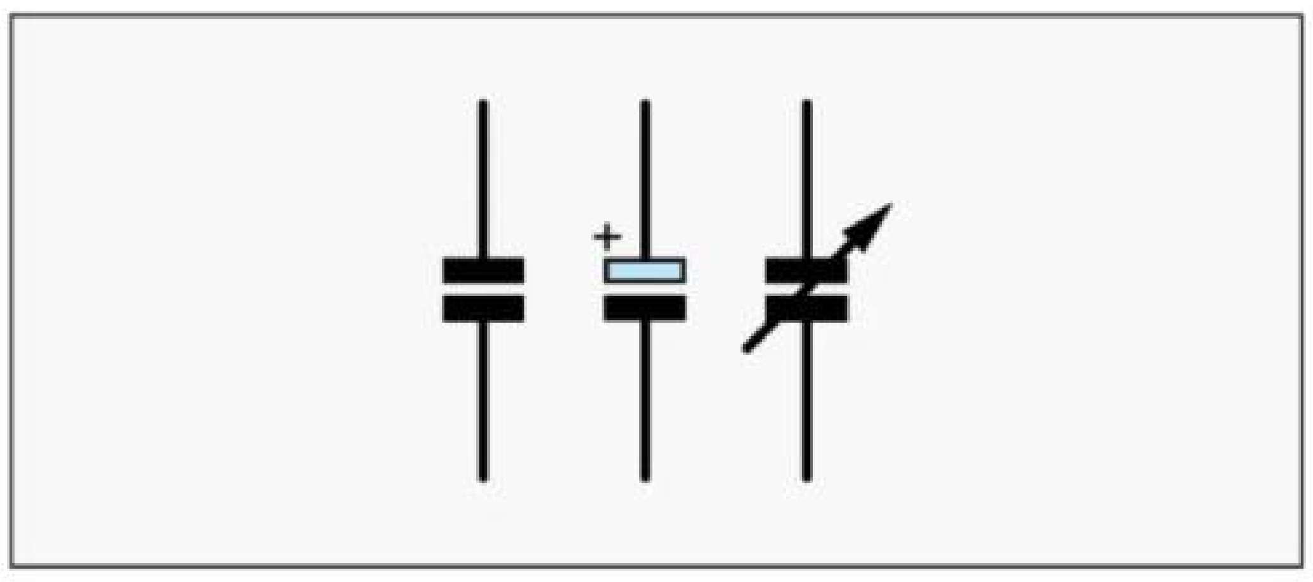


Fig.5. Different capacitor symbols (left to right): plain unpolarised, electrolytic (polarised) and variable.

The capacity of a capacitor is called its 'capacitance', which is measured in farads, symbol F. One farad (1F) is a huge amount of capacitance, so most capacitors are measured in microfarads (1µF, a millionth of a farad), nanofarads (1nF, a billionth of a farad), or even picofarads (1pF, a trillionth of a farad). In the case of our 555 astable and monostable circuits, we use two different capacitors, one with a value of 100µF, and one that is 100nF.

Capacitors also come in two major categories, termed polarised and non-polarised. Non-polarised capacitors can be used in either orientation, meaning that both pins can handle positive and negative voltages, a bit like a filament lightbulb. Polarised capacitors, however, can only be used in one orientation, with one pin being the positive pin, and the other being the negative pin – in this sense they are similar to a battery, it matters which way you connect them. If a polarised capacitor is inserted incorrectly, it can result in the breakdown of the capacitor, and in some cases, they can burst! This is not recommended – the capacitor is ruined and the smell can be awful!

What are LEDs?

Light-emitting diodes, LEDs for short, are small semiconductor devices that, when powered, produce light. Unlike old-fashioned light bulbs which use a tungsten filament, LEDs do not rely on heating a small coil of wire to produce light, but instead take advantage of energy levels in semiconductor materials to directly convert electricity into light. The finer details of this are way beyond the scope of this article, but the important points are they are compact, cheap, efficient and can be made to produce different colours.

LEDs are polarised, meaning that they only work when current flows from the positive terminal (the anode) to the cathode (the negative terminal). This means that they must be inserted the correct way during soldering, otherwise they won't light up. Fig.7 shows the symbol for an LED.

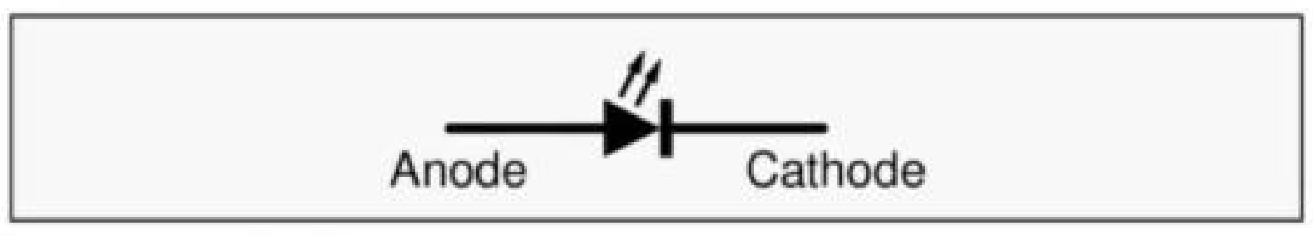


Fig.7. Diode schematic symbol.

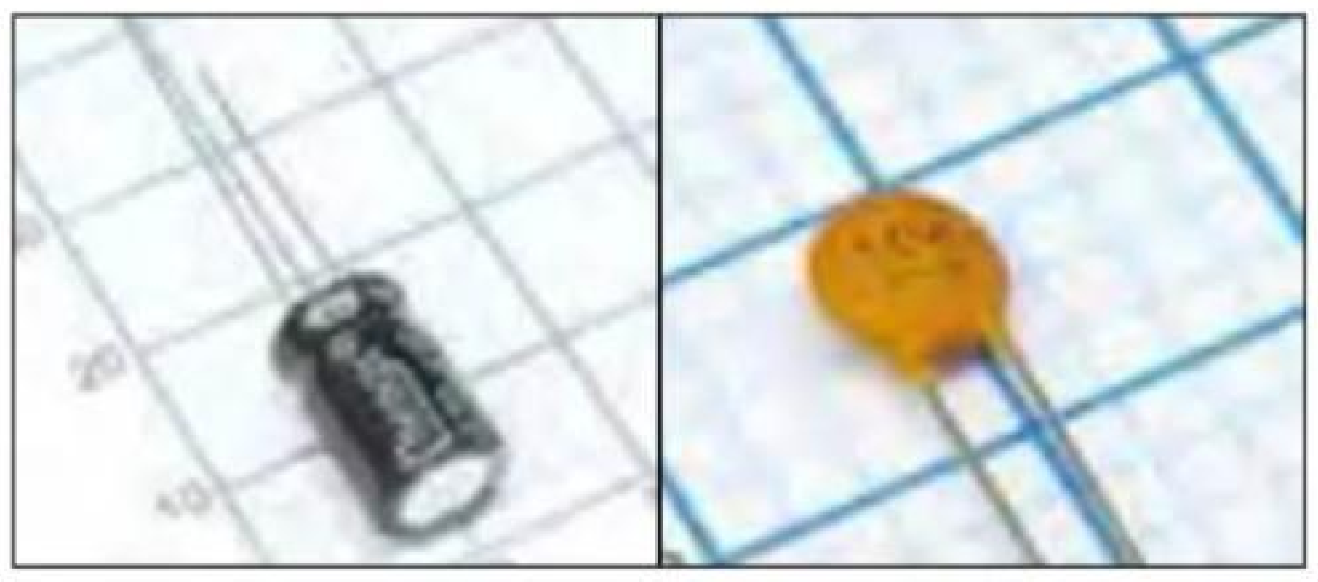


Fig.6. (left) Electrolytic capacitor – note different length leads; shorter is negative connection, (right) ceramic capacitor.

When using LEDs, it is critical to make sure that a series resistor is used, as, unlike light bulbs, LEDs will try to conduct as much current as possible. That means if an LED is directly powered by a power source, they will fry themselves faster than you can blink. Thus, a resistor placed in series with the LED limits the current that can flow through the LED, thereby preventing it from being damaged, as shown in Fig.8. But what size resistor should you use? Well, there is a formula that can help us figure that out exactly, and it is very simple too.

$$R = \frac{V_{in} - V_f}{I_{LED}}$$

To use this formula, we have to decide on what current we want going through the LED (I_{LED}), what forward voltage the LED (V_f) has, and what voltage we are applying to our circuit (V_{in}). When deciding the current, we need to make sure that it is well below the maximum forward current of the LED, otherwise it will burn out. But the brightness of the LED depends on that forward current, so you need to decide how bright you want your LED. In the case of MitchElectronics kits, forward currents are typically chosen to be around 50% of the maximum safe forward current. The current through an LED is usually measured in thousandths of an amp, or 'milliamps', written as 'mA' (the 'm' must be lower case).

The next step is to find out the forward voltage of your LED, and this can be found in its datasheet. In the case of our 555 circuits, we will be using red LEDs which have a forward voltage drop of $V_f = 2V$.

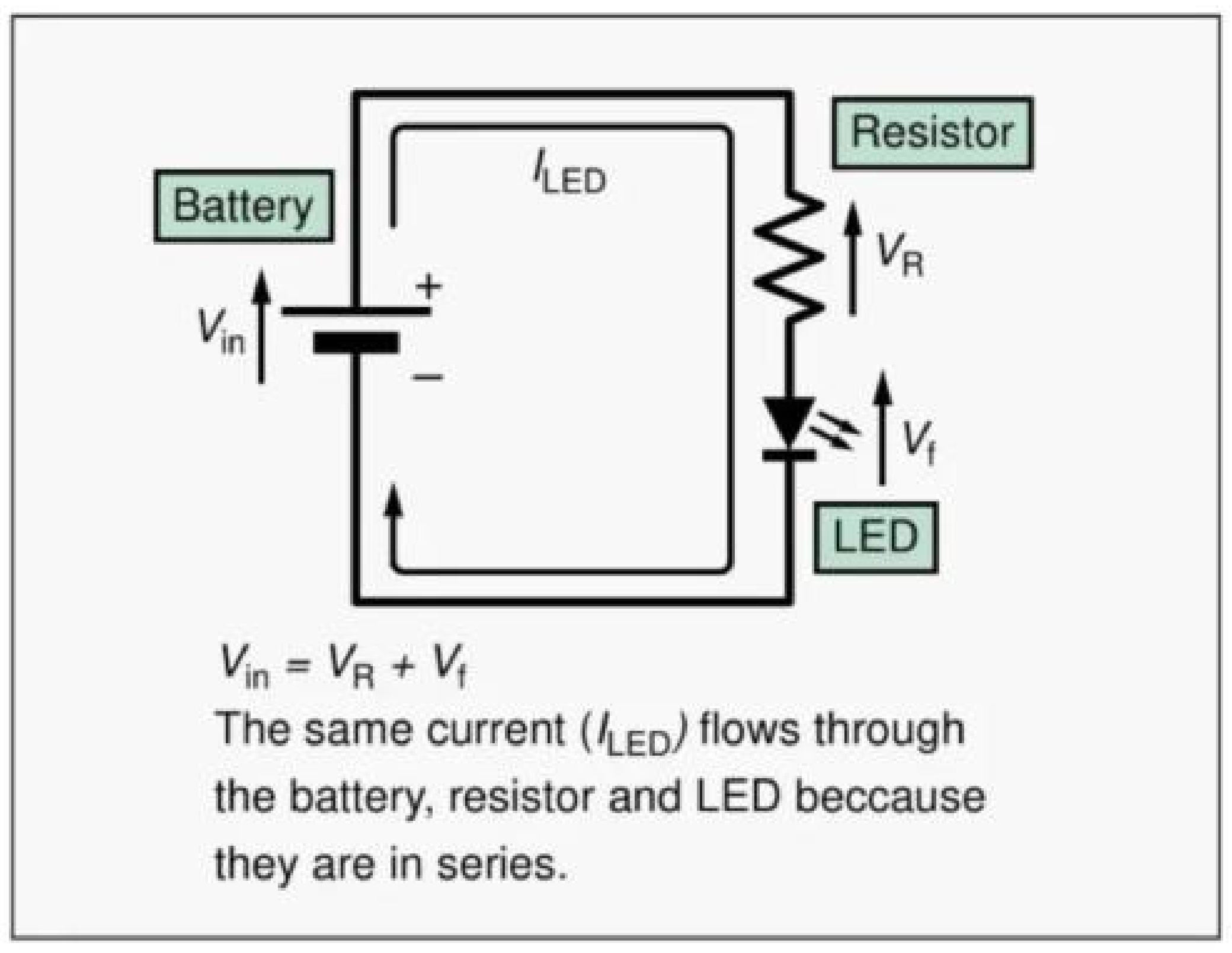

Battery
I_{LED}
Resistor
V_{in}
+
–
V_R
V_f
LED
$V_{in} = V_R + V_f$
The same current (I_{LED}) flows through the battery, resistor and LED beccause they are in series.

Fig.8. Series resistor and LED configuration.

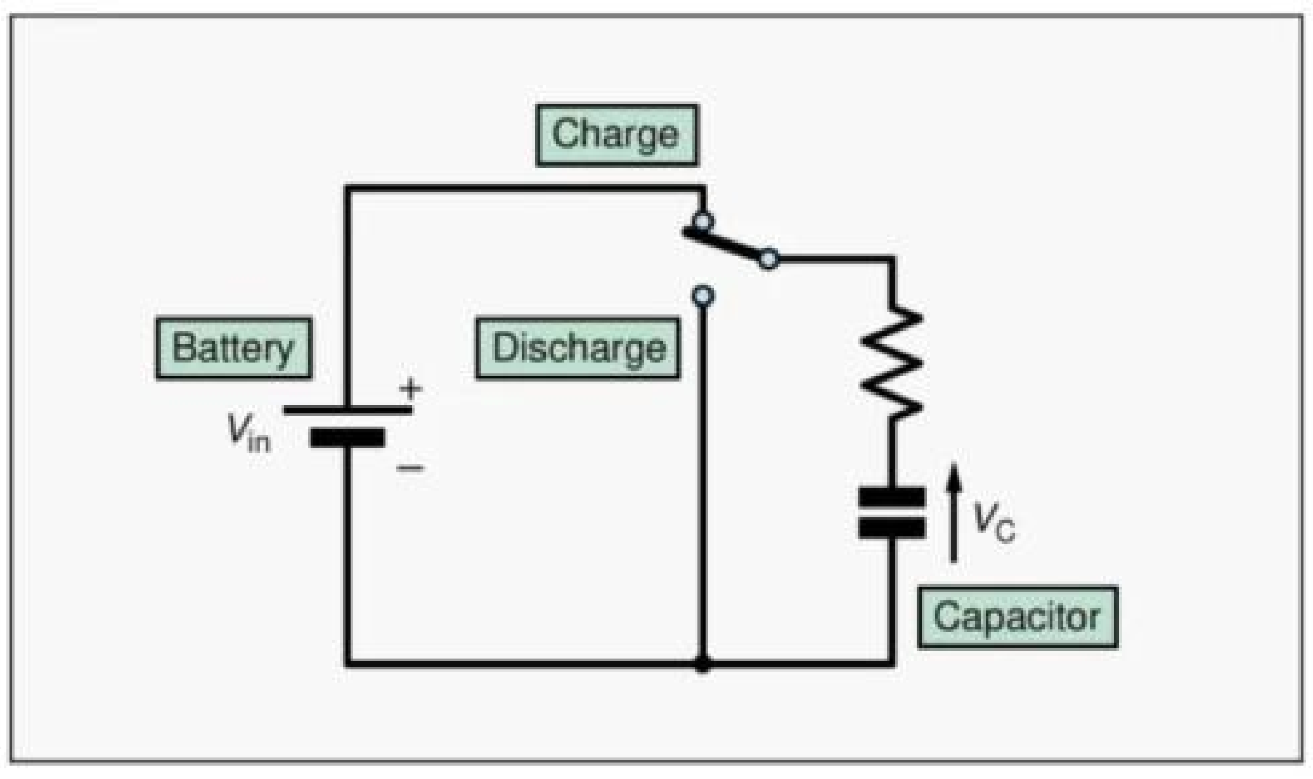


Fig.9. RC charging/discharging circuit.

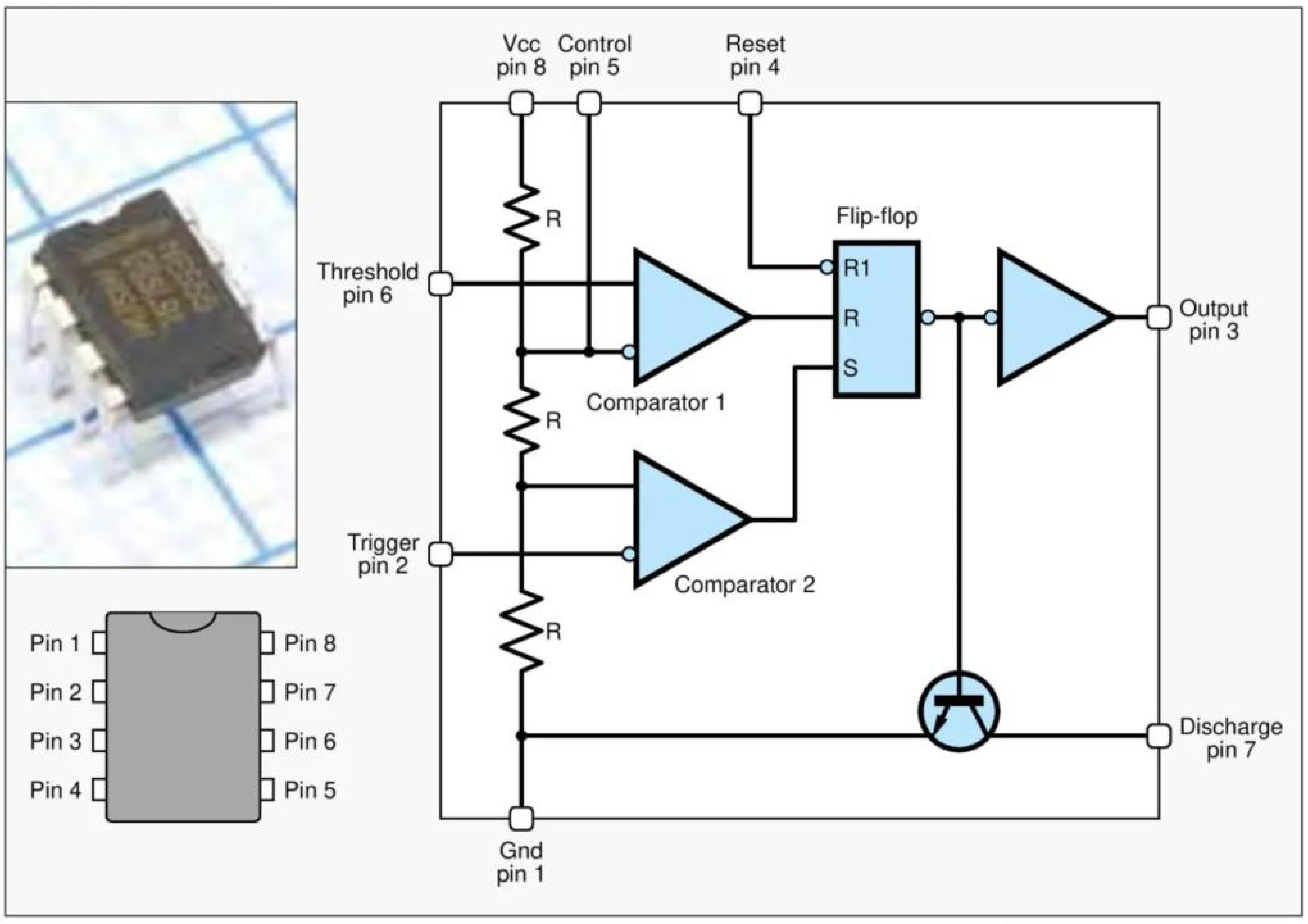


Fig.11. 555 timer: (left) classic 8-pin DIL through hole package and (right) internal structure (right).

This figure means that when a voltage is applied across our LED circuit, the voltage across the LED will always be equal to this forward voltage drop. The crucial insight here is that the input voltage to an LED circuit must be greater than this forward voltage.

Finally, plug these numbers into the above equation, and you get the size of resistor you need. For example, if a red LED (forward voltage of 2V) is used with a 5V supply and needs a forward current of 5mA, the resulting resistor would be 600Ω.

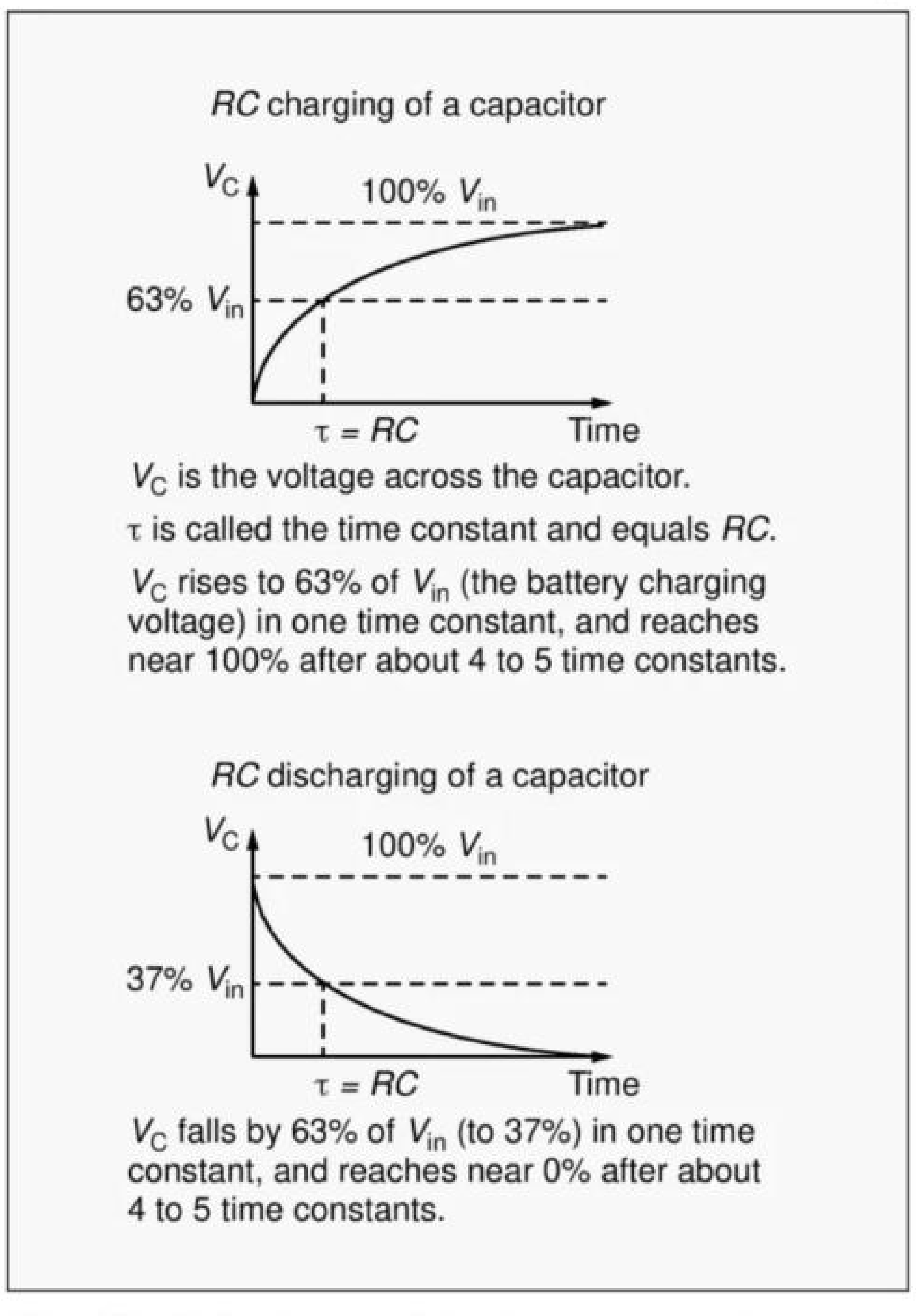
$$R = \frac{V_{in} - V_f}{I_{LED}} = \frac{5-2}{0.005} = 600\Omega$$

What is an RC circuit?

A resistor-capacitor, or *RC* circuit, is one that consists of a resistor and capacitor in series (Fig.9). A capacitor connected to a power source will instantly charge up to the battery voltage, but if a resistor is placed in series, this charging takes time, and the voltage rise across the capacitor follows a very specific curve (see the graph in Fig.10). Likewise, a capacitor that is short-circuited will instantly discharge, but discharging a capacitor through that same resistor will see this voltage fall with the same (but inverted) curve.

The time it takes for the voltage to rise and fall for *a given RC* value is called the time constant (τ, Greek lower-case 't'). For a particular *RC* value, it is always the same time, and this makes *RC* circuits extremely useful in timing applications. The equation that relates the resistance and capacitance to the charging and discharging time constant is simply:

$$\tau = RC$$



V_C is the voltage across the capacitor.

τ is called the time constant and equals *RC*.

V_C rises to 63% of V_{in} (the battery charging voltage) in one time constant, and reaches near 100% after about 4 to 5 time constants.

V_C falls by 63% of V_{in} (to 37%) in one time constant, and reaches near 0% after about 4 to 5 time constants.

Fig.10. RC charge/discharge graph.

Important note on the time constant in this equation: it actually refers to the time needed to charge the capacitor to around 62% of the input voltage. Why this is the case is to do with mathematics involving exponential functions, which is beyond the scope of this article. A good rule of thumb is that a capacitor will charge or discharge completely (or to around 99%) in about four to five time constants (5×*RC*).

What is the 555 timer?

The 555 timer is one of the most famous integrated circuits, and there is good reason for this. In fact, the 555 timer is so popular that, despite having been first sold in 1972, it is still in production, with millions produced each year.

The 555 timer is a chip that consists of two internal comparators, a flip-flop, discharge transistor, and three resistors (see Fig.11) which, when used together, can make a whole range of different timing circuits. Don't worry if you are not sure how flip-flops or transistors work – we will cover them in later articles. For now, the point is we have an IC with a box of tools that enable us to make timing circuits.

While we don't need a thorough working knowledge of the inside of a 555 to use it effectively, an overview of its essential characteristics is helpful. The Output (pin 3) goes high (close to the supply voltage, V_{CC}) when the Trigger input (pin 2) *falls below* 1/3 of V_{CC}. The Output stays high until the Threshold input (pin 6) is activated by a voltage *above* 2/3 of V_{CC}, at which point the Output goes low *and* the Discharge transistor is turned on.

The discharge transistor (pin 7) acts like a switch, discharging the charge stored in an external timing capacitor (C_1) when it is turned on.

Power is supplied via pin 8 for V_{CC} and pin 1 for 0V or ground. For now, we can ignore the effect of the Reset (pin 4) – we will cover it in later articles – just connect it to V_{CC}.

Interestingly, many believe that the 555 timer gets its name from the three internal 5kΩ resistors, but in fact, the name was chosen arbitrarily.

In this article, we are going to use the 555 timer to create an astable and monostable timer. Both of these circuits will take advantage of *RC* circuits to control timing, potentiometers to allow for adjusting the timing without needing to replace components, and LEDs to show the output.

How does a 555 astable work?

Before we dive into the circuit function, we first need to study the circuit diagram for the 555 astable circuit (see Fig.12). The *RC* circuit is made up of R_1, RV_1, and C_1, while the LED (D1) is connected to the output of the 555 timer via resistor R_2. You will also notice that the Control pin of the 555 timer (pin 5) is connected to a small capacitor (C2), this is needed to provide stability to the internal components of the 555 timer.

Assuming that the circuit has just been powered by a 9V battery, the first thing that happens is that the voltage across C_1 is 0V and the output of the 555 is high. This also puts the 555 into its set state, whereby the discharge pin is shut off, and current can flow through R_1 and RV_1, and into capacitor C_1.

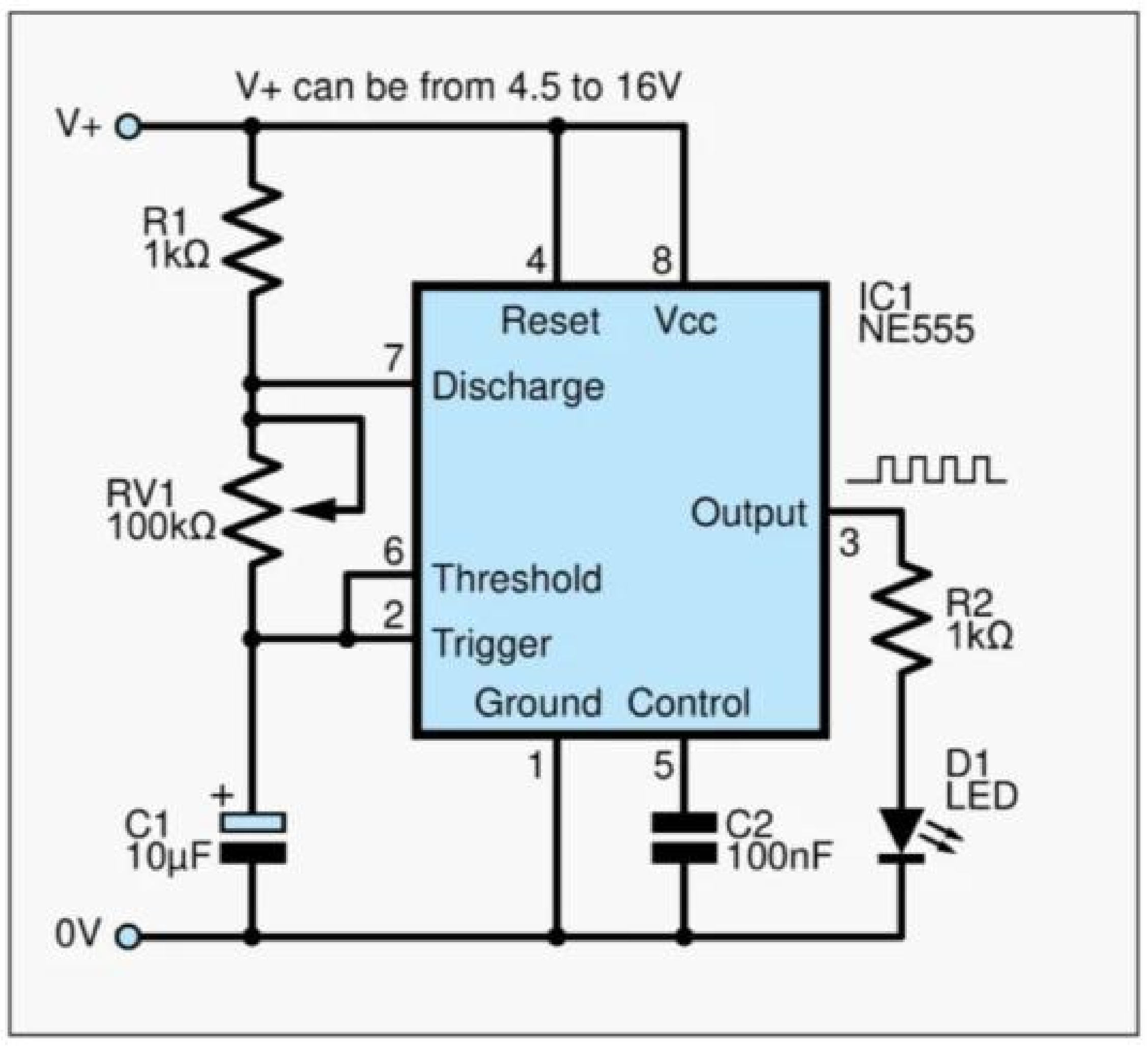


Fig.12. 555 Astable Circuit.

This current flow charges up C_1, resulting in the voltage across C_1 rising. The speed at which the capacitor C_1 charges up depends on the resistance of R_1 plus the potentiometer RV_1, because resistance resists current flow. Thus, if R_1 plus RV_1 has a low resistance, the capacitor C_1 will charge quickly, and if RV_1 has a large resistance, then capacitor C_1 will charge slowly.

However, this voltage across C_1 will eventually go beyond the trigger level of the 555 timer, and when this happens, the output of the 555 timer will go low. At this point, the internal discharge circuit will activate, and this will see capacitor C_1 begin to discharge through RV_1 and into pin 7. This discharging causes the voltage across C_1 to fall.

Eventually, the voltage across C_1 will fall below the threshold point of the 555 timer IC, and this causes the 555 timer to turn off its discharge circuit (pin 7) and turn off its output (pin 3). Thus, the capacitor C_1 will begin to charge again, and the entire process of charging and discharging continues to repeat forever. This is called an astable oscillator because it has *two* states that are both *unstable*.

The capacitor voltage compared to the output voltage can be seen in Fig.13, and formula that describes the frequency of a 555 Astable circuit is given by:

$$frequency = \frac{1.44}{(R_1 + 2R_{RV})C_1}$$

If you want to 'cheat' and use a calculator, then you can instead visit: **https://bit.ly/mitch-resources**

How does a 555 monostable work?

The 555 monostable circuit, just like the astable, is made up of an *RC* circuit (R_2, RV_1 and C_1) and an output LED – see Fig.14. However, unlike the astable, only pin 6 and 7 (threshold and discharge) are connected to our *RC* circuit, and pin 2 (the trigger) is connected to a switch and resistor combination. If the switch isn't being pushed, then pin 2 is pulled up to 9V through the resistor R_1, and this deactivates the trigger in the 555 as the trigger is *active low* (meaning that it needs to be 0V to trigger).

Under normal conditions, the 555 IC is in its discharge mode, meaning that the capacitor C_1 cannot charge (as the current flows thorough R_2 and RV_1 into the discharge pin instead of going into the capacitor C_1). However, when the switch is pushed, the voltage at pin 2 (the trigger) of the 555 causes it to go into its set mode, which turns off the discharge pin. Now, current starts to flow into C_1, causing the voltage to rise across it. In this set mode, the output of the 555 also switches on, providing 9V and turning on LED D1.

Eventually, the voltage across C_1 will reach 2/3 of the supply voltage, and when this happens, the 555 will be triggered into its reset mode, where the capacitor C_1 is drained rapidly through pin 7 (discharge). This also turns off the output of the 555 timer, thereby turning off the LED. See Fig.15 for a visual explanation of the monostable.

This circuit is called a monostable because it is only stable in one state (hence, mono or one). When triggered into its set state, it can only remain there until the capacitor has charged up significantly, and this second state is unstable. To calculate the on period (*T*), use the following:

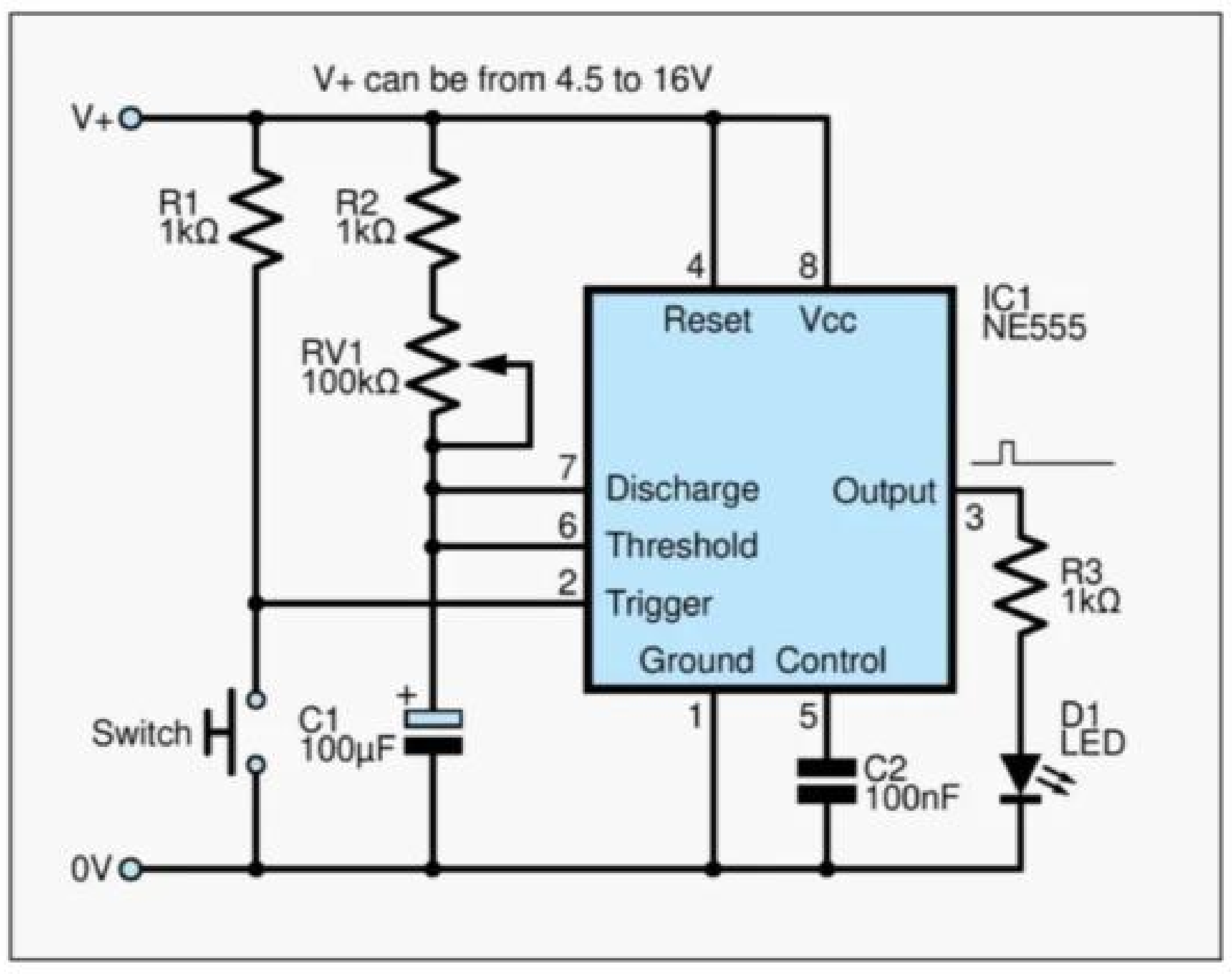


Fig.14. 555 Monostable Circuit.

$$T = 1.1 \times RC$$

Where: *T*, measured in seconds is the width of a monostable pulse
R, measured in ohms is equal to $R_2 + RV_1$ (vary RV_1 to vary *T*)
C, measured in farads is equal to C_1

Again, if you want to use a calculator, go to: **https://bit.ly/mitch-resources**

Build advice

When building the MitchElectronics 555 Astable and Monostable kits, it is important to triple check the position of components and their orientation. All MitchElectronics boards are double-sided and through-hole plated, so while this means that they are extremely strong and pads don't break off, it does mean that soldering mistakes can be a little tricky to undo (not impossible, but certainly challenging).

It is highly recommended that the first parts soldered to the PCB are the smallest components, not by width and length, but by height. So, in this case, it is best to start with the resistors, followed by the IC socket. Then proceed with capacitors, LEDs and finally, the potentiometer. If you have trouble with getting solder to stick to components and pads, then a bit of cleaning with IPA followed by some flux can go a long way.

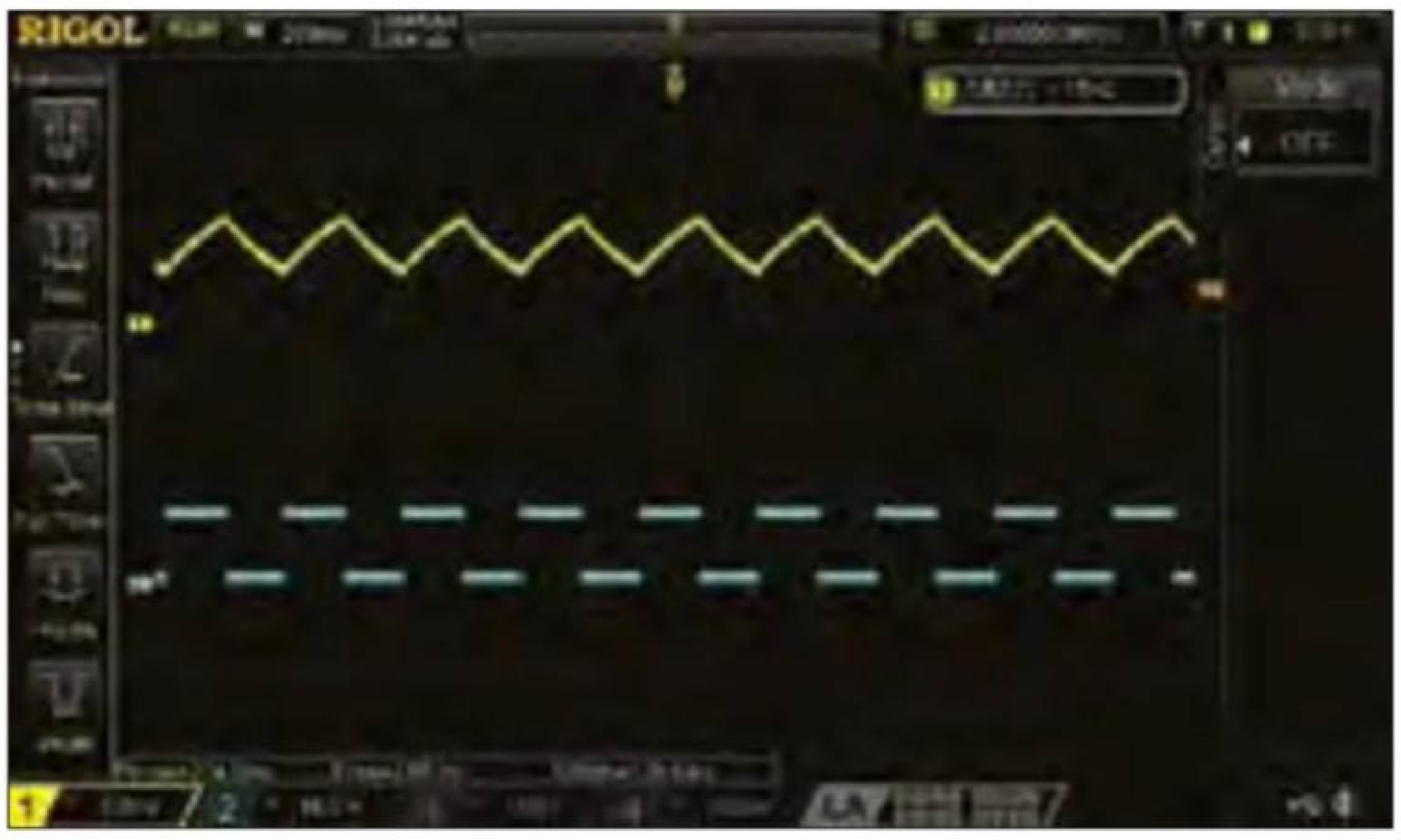


Fig.13. Oscilloscope output comparing capacitor voltage (yellow) to output voltage (blue).

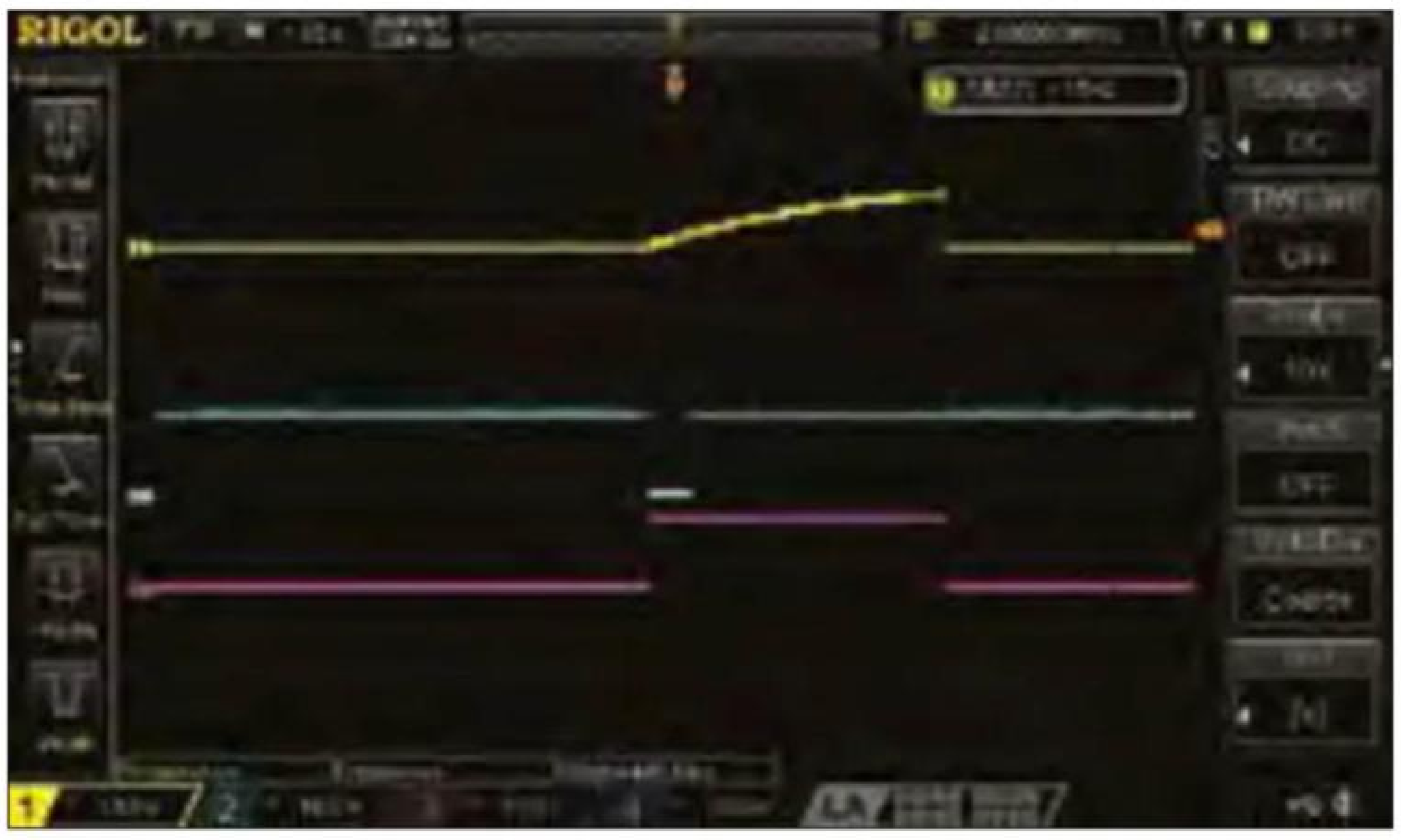


Fig.15. Oscilloscope output showing capacitor voltage (yellow), trigger voltage (blue), and output voltage (purple).

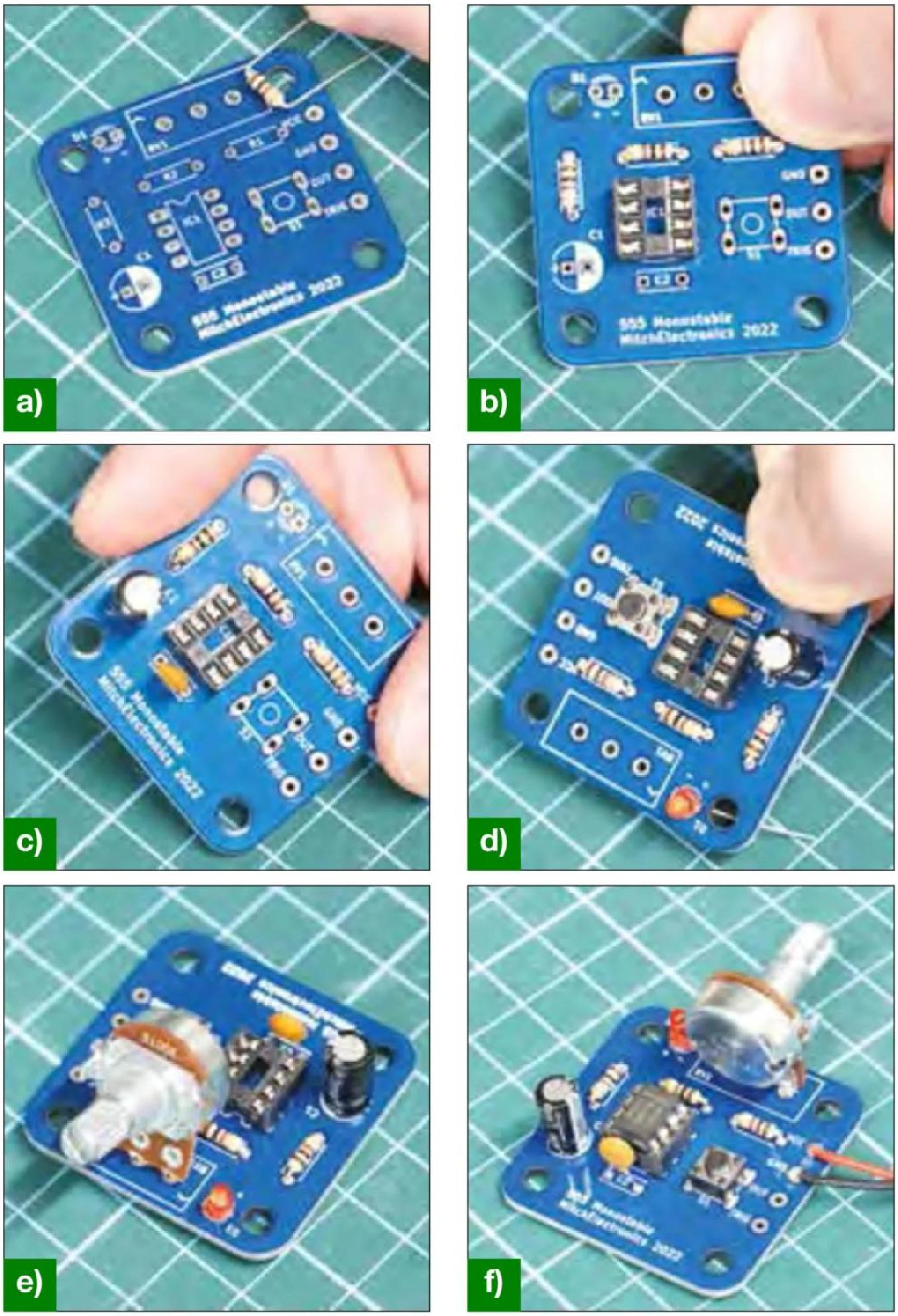


Fig.16. Construction stages of the kit: a) start with the smallest flattest components – resistors, b) next, the IC holder, c) now add capacitors – check polarity of the electrolytic one!, d) now the (polarised) LED, e) the potentiometer... and last, f) add the power leads.

Be extra careful when inserting the LED and electrolytic capacitors, as these are polarised components. It should also be noted that MitchElectronics kits follow the standard KiCad PCB design software format for pads, meaning that with LEDs, the positive pin is the circular pad, and not the square pad. However, for electrolytics, the positive pin is the square one, and not the round one!

Fig.16 provides a step-by-step overview of circuit assembly.

When inserting the 555 IC into the socket, ensure that it is oriented the correct way, otherwise you may damage the chip when you power it up. Finally, make sure to discharge any static electricity which may be dancing around your body before constructing the kit, as this can damage the chip. The fastest way to do this is to touch something grounded, such as an exposed radiator pipe.

If you want to build an SMD version of these kits, you can also explore the MitchElectronics 555 Astable and Monostable SMD Trainers on our website.

Powering the project

Powering the 555 circuits is dead easy thanks to the inclusion of a PP3 battery connector. However, this doesn't have to be used, and can be replaced with wires connecting to an external power source. You must make sure the voltage range is between 4.5V and 16V and applied with the correct polarity!

Testing the project

To test the boards, you don't require any specialist equipment; eyeballs are more than enough to get the job done. If all goes well, you should see the LED blink when powering the astable circuit, and if it appears that the LED just stays on, try adjusting the potentiometer until you see it blink. With the monostable circuit, you should see the LED turn on after pushing the button, and if you don't, try adjusting the potentiometer and pushing the button again.

When operating the astable and monostable at high frequencies / short periods, an oscilloscope can be used to observe signals in the circuit – see Fig.18. A scope can also help to show the nature of charging circuits, as well as diagnosing any potential problems.

If you are exceptionally worried about damaging your circuit, you can opt to use an external power supply with a current limiter, as shown in Fig.19. Start by setting the current limiter to a very low value (such as 50mA), and then gradually raise the voltage. If you see that the current limiter quickly maxes out, then you may well have a short circuit and you need to check your soldering.

555 ASTABLE

555 MONOSTABLE

Fig.17. Scan these QR codes to see additional kit instructions.

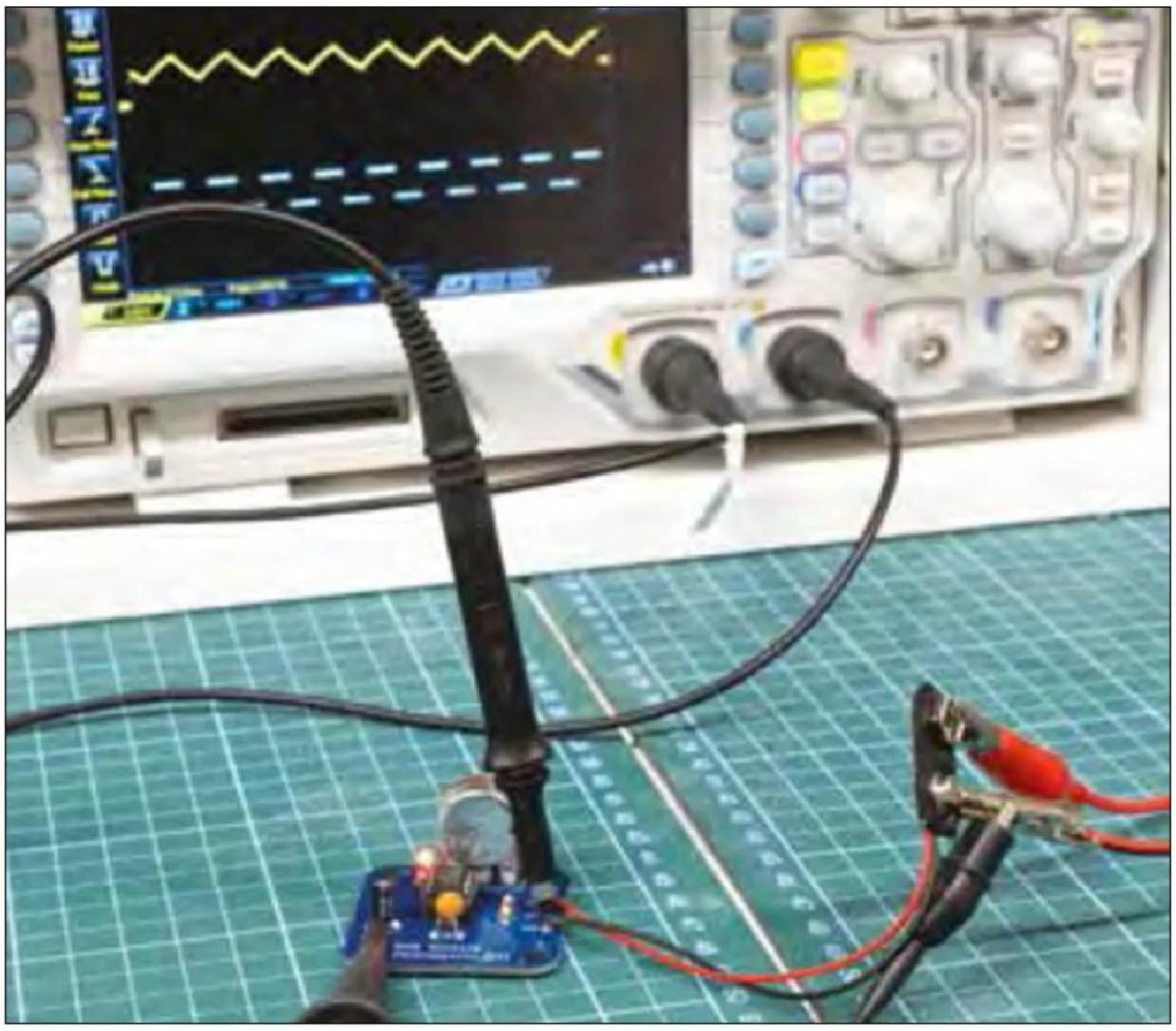


Fig.18. A scope can be handy when testing the boards, but you can build these kits successfully without one.

Troubleshooting

Not much can go wrong with these circuits, but that isn't to say that mistakes can't happen. If you find that the LED doesn't blink, then the first thing you need to check is the orientation of the LED. Using a continuity probe on the LED can tell you if you have the orientation of the LED correctly, and a multimeter can be used to measure the output voltage of the 555 chip (pin 3).

If the LED seems to be fine, check the orientation of the IC, as it is quite easy to insert these the wrong way. If the IC is correctly positioned, then the next logical step is to check the orientation of the electrolytic capacitor. Assuming all this checks out, then it is possible that the IC may have been damaged, but this is unlikely as the 555 timers used in MitchElectronics kits are BJT variations, which are far less susceptible to static damage.

Simulation

Simulations for both kits are available on the MitchElectronics website (see the website's resource page or each kit's packaging for a QR code – and also Fig.17). These simulations are powered by the free circuit simulator Falstad Circuit Simulator, and provide an excellent visual reference of how these kits work. Furthermore, due to the simplicity of the 555 circuits, the simulation is a near-perfect representation of the real circuit! An example simulation is shown in Fig.20.

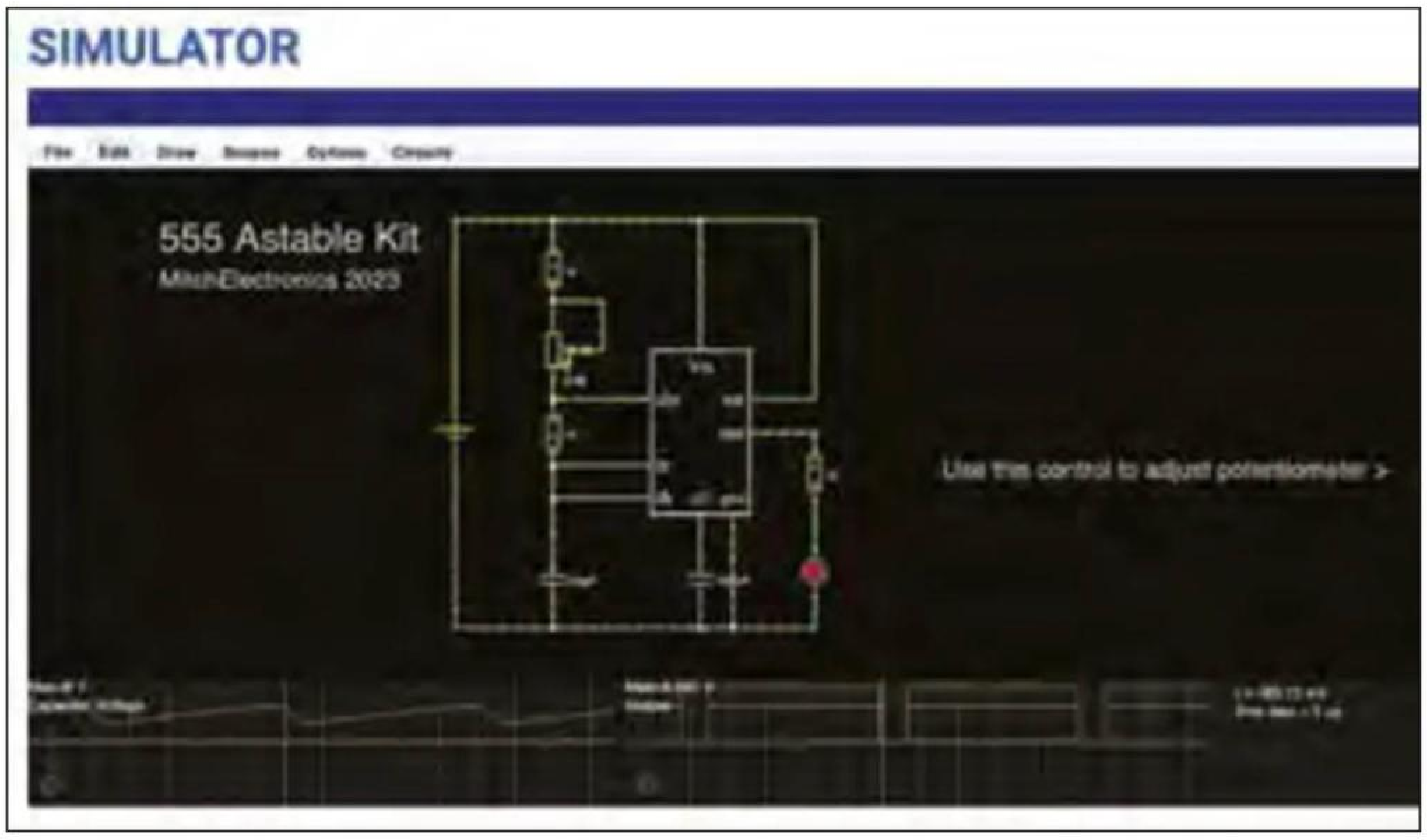


Fig.20. Watch and control simulations of the circuits on the MitchElectronics website.

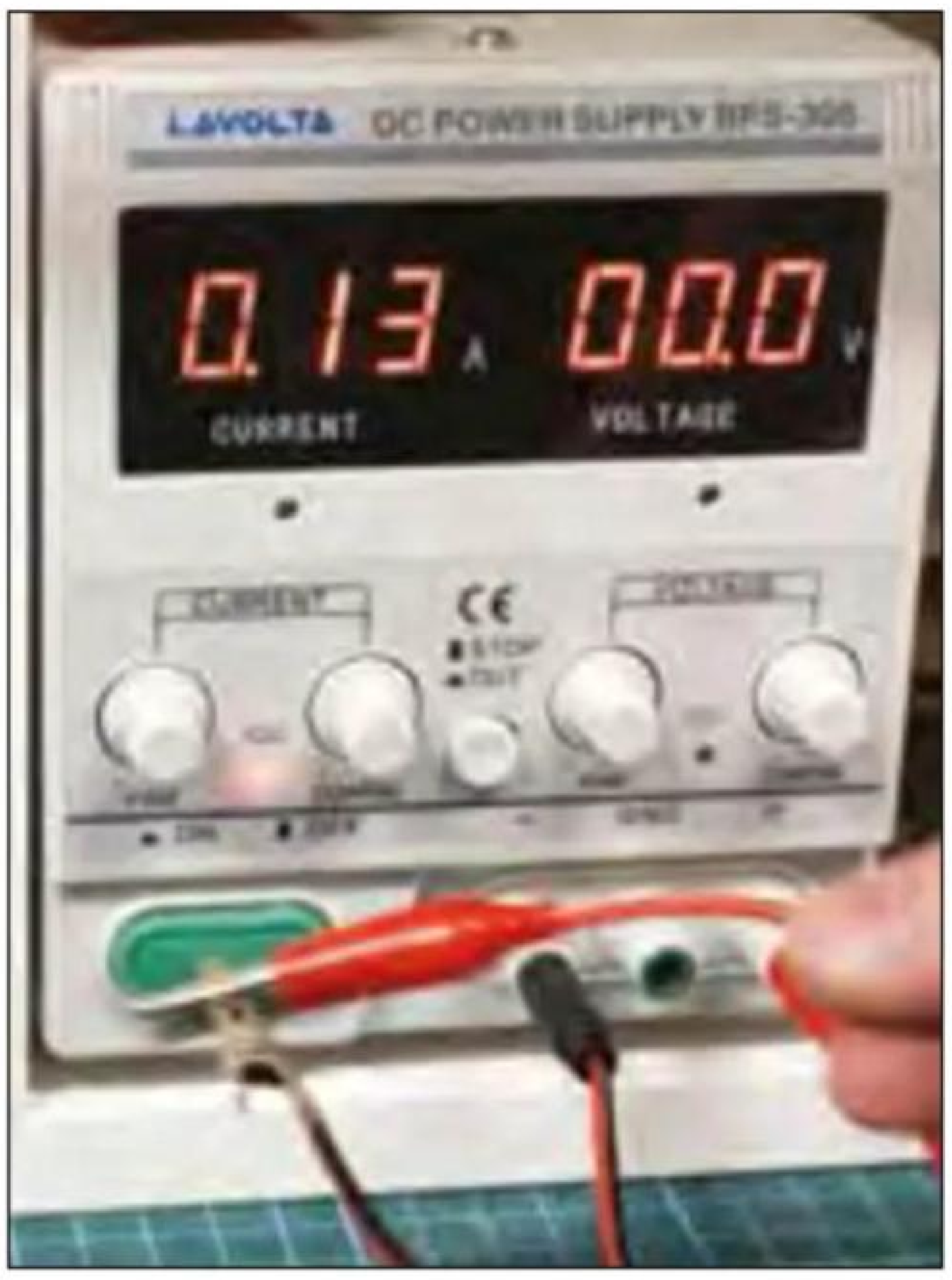


Fig.19. You can use the current limiter on a power supply to prevent damage.

Parts list

The parts needed to build the 555 Astable and Monostable circuits are shown in Fig.21 and Fig.22; but for those who want to build the project from their own parts, use the following list.

555 Astable
1 x 8 DIP socket
1 x 555 IC
1 x 100nF capacitor
1 x 10μF capacitor
2 x 1kΩ resistor
1 x 100kΩ potentiometer
1 x 3mm red LED
1 x PP3 connector
1 x PCB

555 Monostable
1 x 8 DIP socket
1 x 555 IC
1 x 100nF capacitor
1 x 10uF capacitor
3 x 1kΩ resistor
1 x tactile switch
1 x 100kΩ potentiometer
1 x 3mm red LED
1 x PP3 connector
1 x PCB

Taking the project further

At this point, you may be wondering now that you have a circuit which blinks and one that stays on for a set period of time, what can you do with it? Well, these circuits have plenty of use in the real world, so you won't struggle to find practical applications for the astable and monostable.

The astable is great as a clock source for digital circuits which require a regular pulse to function correctly. Of course, such a clock pulse will often need to be much faster than what is provided in the

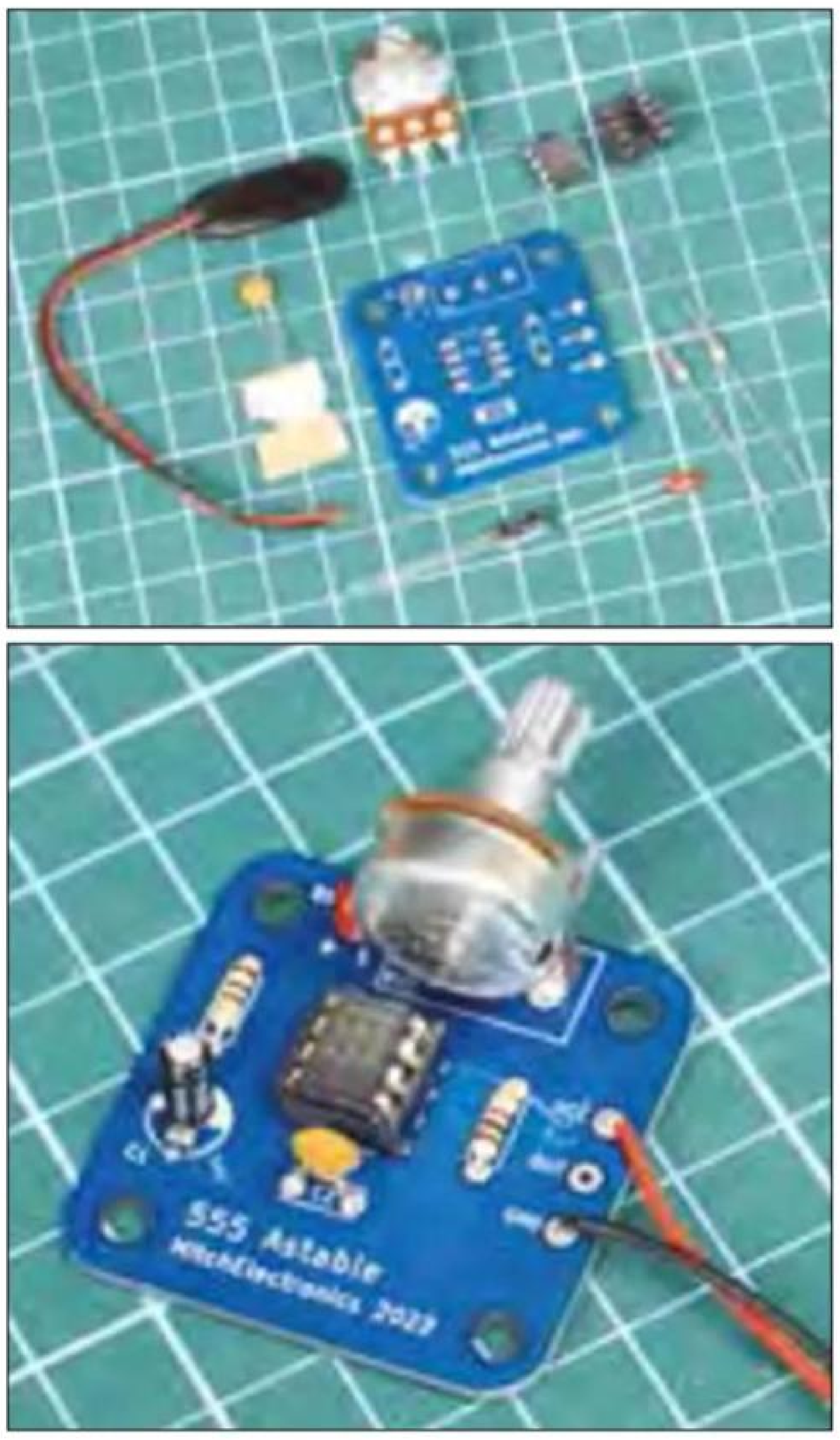


Fig.21. MitchElectronics 555 Astable kit and completed PCB.

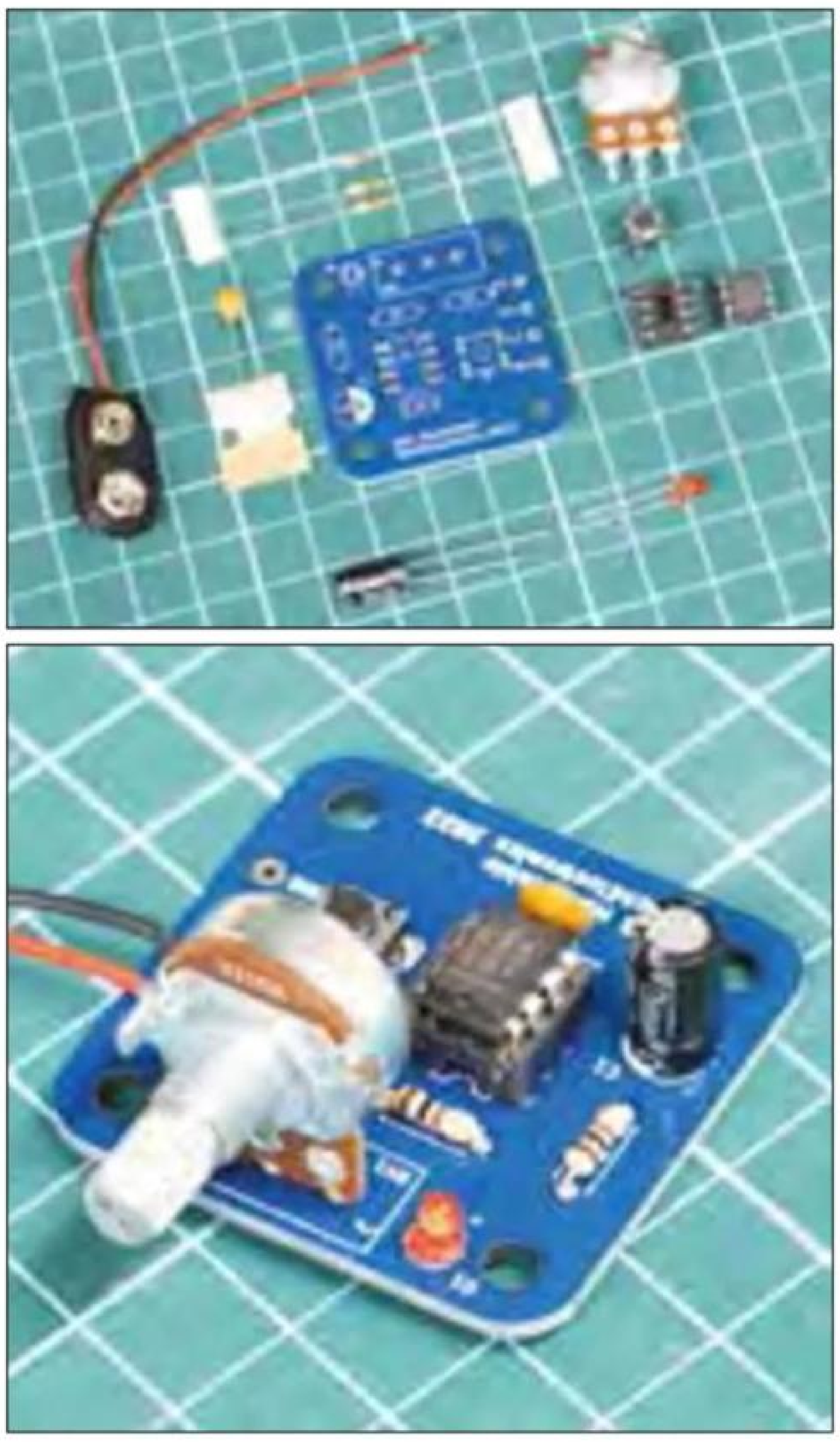


Fig.22. MitchElectronics 555 Monostable kit and completed PCB.

MitchElectronics kit, so you can reduce the value of C_1 to make the 555 oscillate much quicker. The slow blinking nature of the 555 astable can also be useful for optical projects, such as lights placed on the back of a bike to alert other users, or as a model railway warning signal indicating oncoming trains.

The monostable can be useful for applications involving one-shot actions, such as a water valve which needs to deliver a specific amount of water before turning itself off. This action can also be useful in digital circuits which ignore accidental repeated presses of a button, such as keyboards and interfaces. The set on period is also useful for keeping car lights on for a minute after parking, so you don't need to try and find your way to your front door in the dark.

If you want to see these projects in action, then consider checking out the upcoming *MitchElectronics and Practical Electronics Video Series*, which will cover this project and more, showing live oscilloscope traces, in-depth building guides, and more.

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https://mitchelectronics.co.uk

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KickStart

by Mike Tooley

Part 14: Legacy logic revisited

Our occasional KickStart series aims to show readers how to use readily available low-cost components and devices to solve a wide range of common problems in the shortest possible time. Each of the examples and projects can be completed in no more than a couple of hours using 'off-the-shelf' parts. As well as briefly explaining the underlying principles and technology used, the series will provide you with a variety of representative solutions and examples along with just enough information to be able to adapt and extend them for their own use.

This instalment explains how the use of 'legacy logic' can provide you with a simple and cost-effective solution to a variety of everyday circuit design problems. We follow the stages in the design process as the author delves deep into his 'junk' component store and shows how a simple Quiz Machine circuit can be constructed at a small fraction of the cost and complexity associated with one of today's most popular microcontrollers.

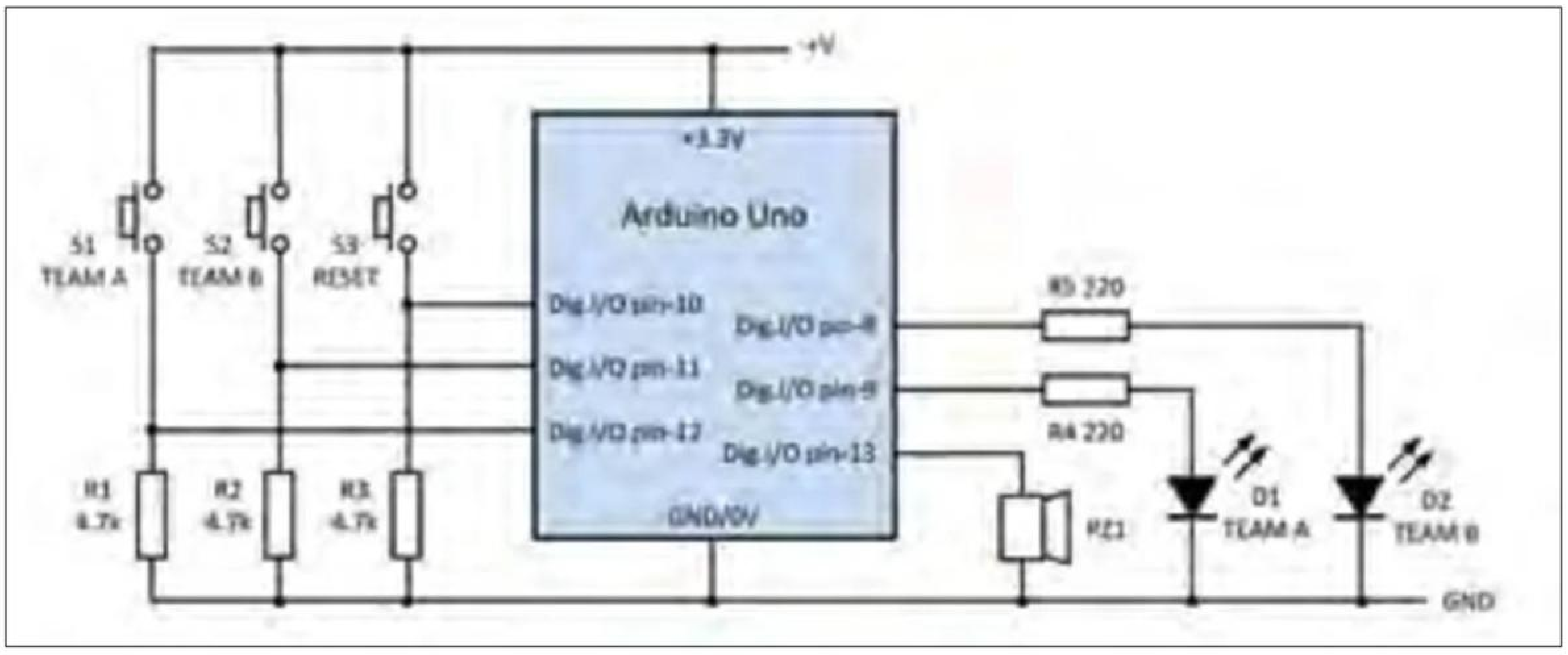

+V
+3.3V
Arduino Uno
S1
TEAM A
S2
TEAM B
S3
RESET
Dig.I/O pin-10
Dig.I/O pin-11
Dig.I/O pin-12
Dig.I/O pin-8
Dig.I/O pin-9
Dig.I/O pin-13
GND/0V
R5 220
R4 220
R1
4.7k
R2
4.7k
R3
4.7k
PZ1
D1
TEAM A
D2
TEAM B
GND

Fig.14.1. The original design concept for the *Quiz Machine*.

When recently tasked with designing a simple *Quiz Machine* I immediately settled on my usual 'go to' solution. An Arduino Uno, together with an LCD display and a few other components should do the job nicely. A prototype was duly assembled and with the addition of a few dozen lines of code it all worked well. Later, and having moved on from the prototype stage with a first iteration of the PCB in front of me, I began to have a few nagging doubts about this solution.

Why legacy logic?

The first issue was the cost. Even without the LCD display this project was going to be expensive and was likely to exceed my original budget by a factor of three. I needed a much simpler low-tech solution, so maybe I shouldn't be using a microcontroller at all. In the end, and after a few 'sleepless nights' I eventually decided on a solution based on a single logic chip that can be purchased for less than 50p and which needs no coding at all!

Revisiting the basic elements of logic

Resorting to my extensive 'junk' component store I discovered a host of logic chips that had been classified as 'worth keeping' (just in case I needed to carry out a repair on some elderly item of equipment) as well as a copious supply of computer panels stuffed with 14, 16 and 18-pin dual-in-line chips. This, then, was going to be my starting point: a quantity of TTL-compatible CMOS devices that had been used in constructional projects of a few decades ago.

The symbols for some basic logic elements are shown, together with their truth tables in Fig.14.2. Note that, while inverters and buffers each have only one input, exclusive-OR gates have two inputs and the other basic gates (AND, OR, NAND and NOR) are commonly available with up to eight inputs. The action of each of the basic logic gates can be summarised as follows:

Buffer

Buffers do not affect the logical state of a digital signal – a logic 1 input always results in a logic 1 output, and a logic 0 input always results in a logic 0 output. Buffers are normally used to provide extra current drive at the output but can also be used to regularise the logic levels present at an interface. Its triangular symbol shape is deliberate – think of it as a digital unity-gain amplifer.

Inverter

Inverters are used to 'complement' the logical state. In other words, a logic 1 input results in a logic 0 output, and vice versa. Just like buffers, inverters also

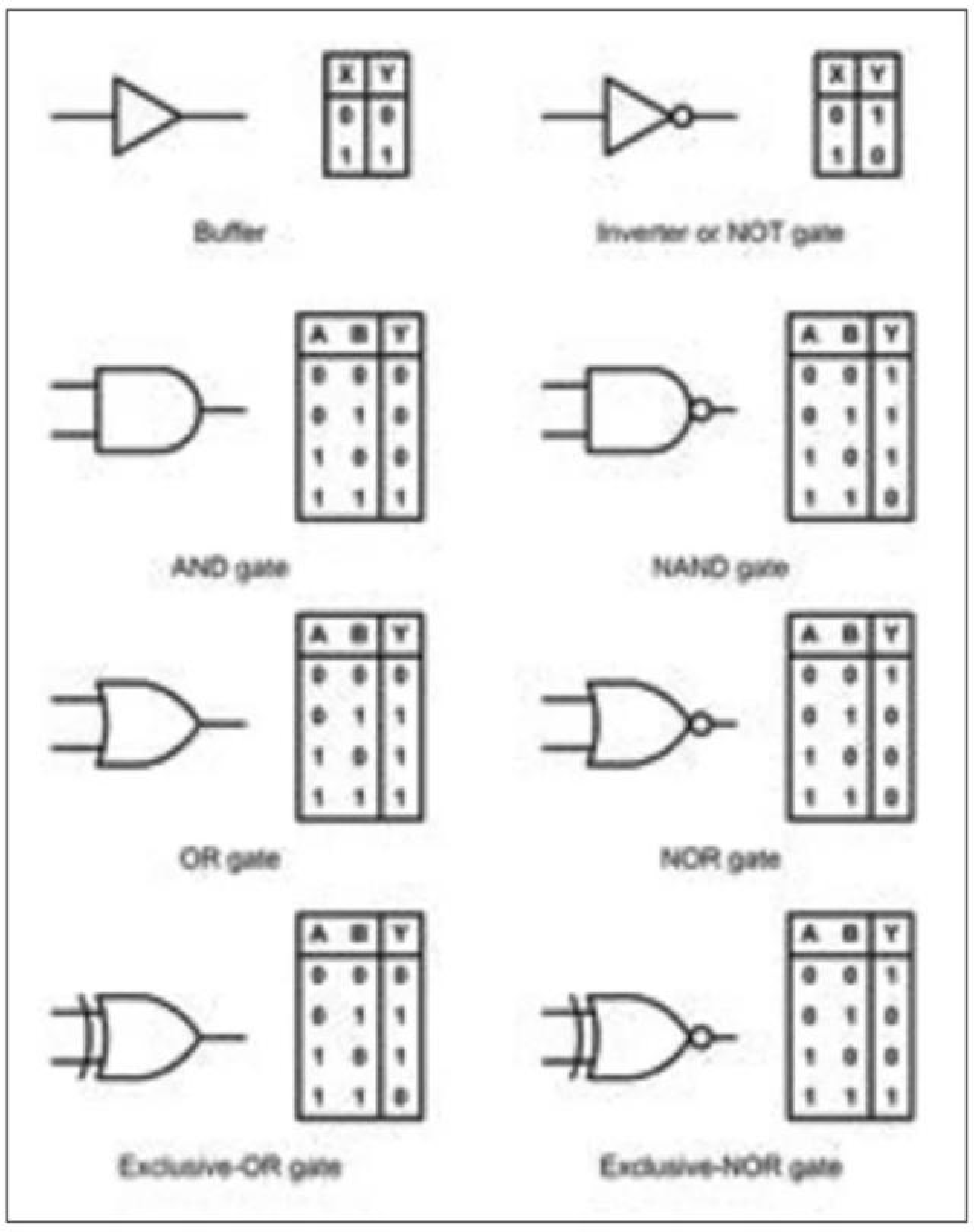

X Y
0 0
1 1
Buffer
X Y
0 1
1 0
Inverter or NOT gate
A B Y
0 0 0
0 1 0
1 0 0
1 1 1
AND gate
A B Y
0 0 1
0 1 1
1 0 1
1 1 0
NAND gate
A B Y
0 0 0
0 1 1
1 0 1
1 1 1
OR gate
A B Y
0 0 1
0 1 0
1 0 0
1 1 0
NOR gate
A B Y
0 0 0
0 1 1
1 0 1
1 1 0
Exclusive-OR gate
A B Y
0 0 1
0 1 0
1 0 0
1 1 1
Exclusive-NOR gate

Fig.14.2. Symbols for basic logic elements, together with their truth tables.

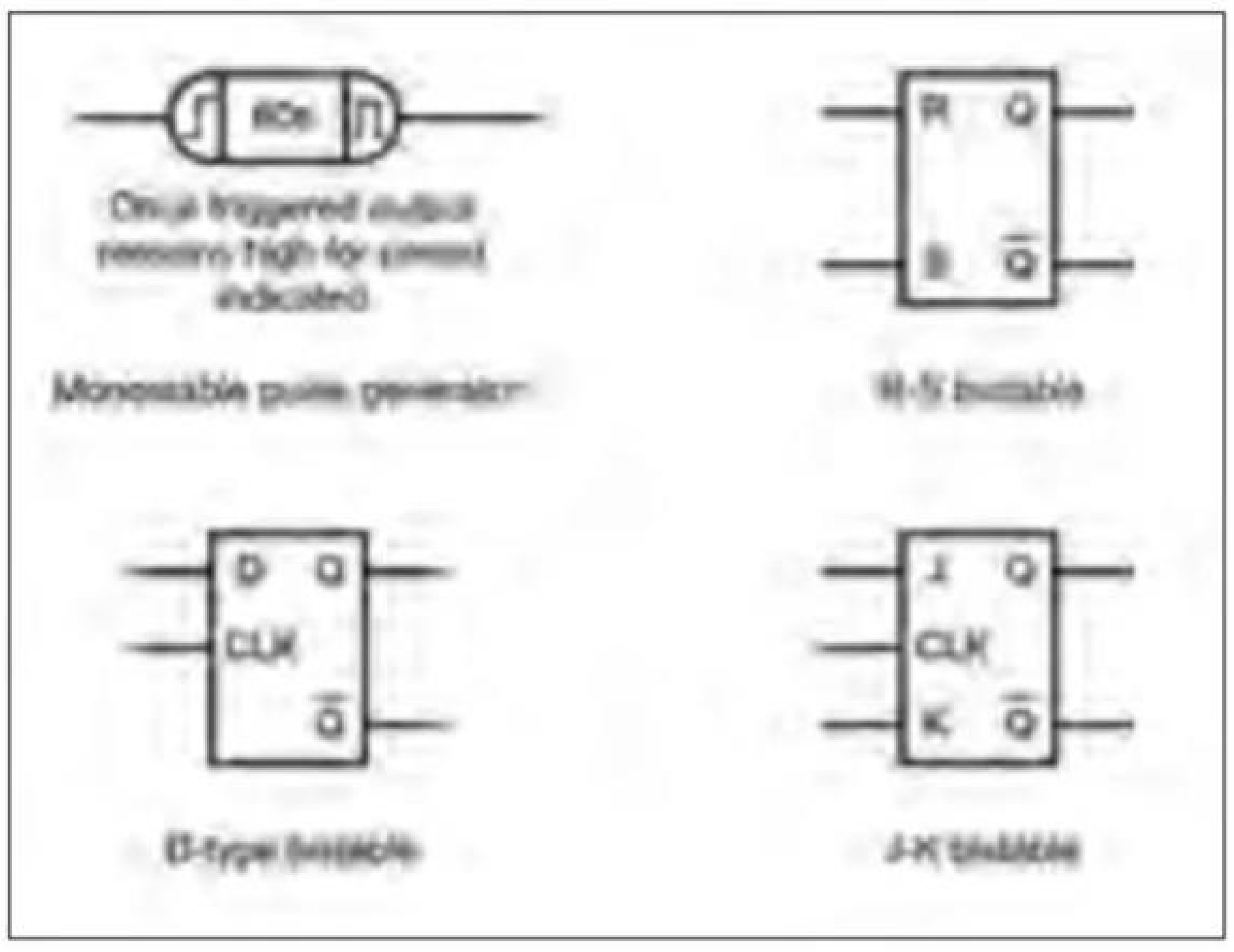


Fig.14.3. Symbols for monostable and bistable elements.

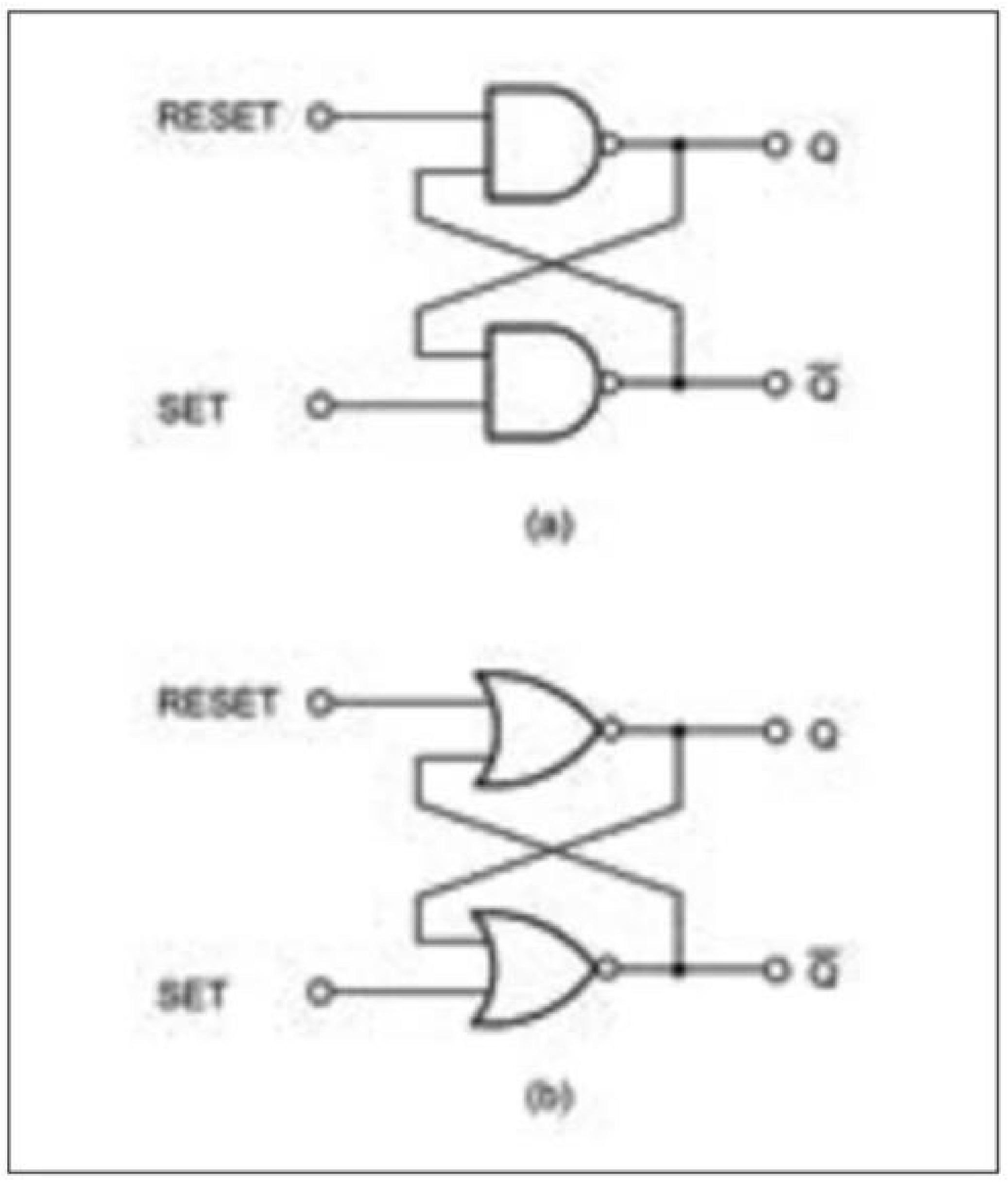


Fig.14.4. Using cross-coupled NAND and NOR logic gates to realise an R-S bistable.

provide extra current drive and are used in interfacing applications, where they provide a means of regularising logic levels present at the input or output of a digital system. The circle indicates inversion.

AND
The output of an AND gate will only produce a logic 1 output when all inputs are simultaneously at logic 1. Any other input combination results in a logic 0 output.

OR
An OR gate will produce a logic 1 output whenever any one or more inputs are at logic 1. Putting this another way, an OR gate will only produce a logic 0 output when all of its inputs are simultaneously at logic 0.

NAND
A NAND gate ('not-AND') will only produce a logic 0 output when all inputs are simultaneously at logic 1. Any other input combination will produce a logic 1 output. A NAND gate, therefore, is nothing more than an AND gate with its output inverted, or put another way, an AND gate followed by an inverter. The circle at the output denotes this inversion.

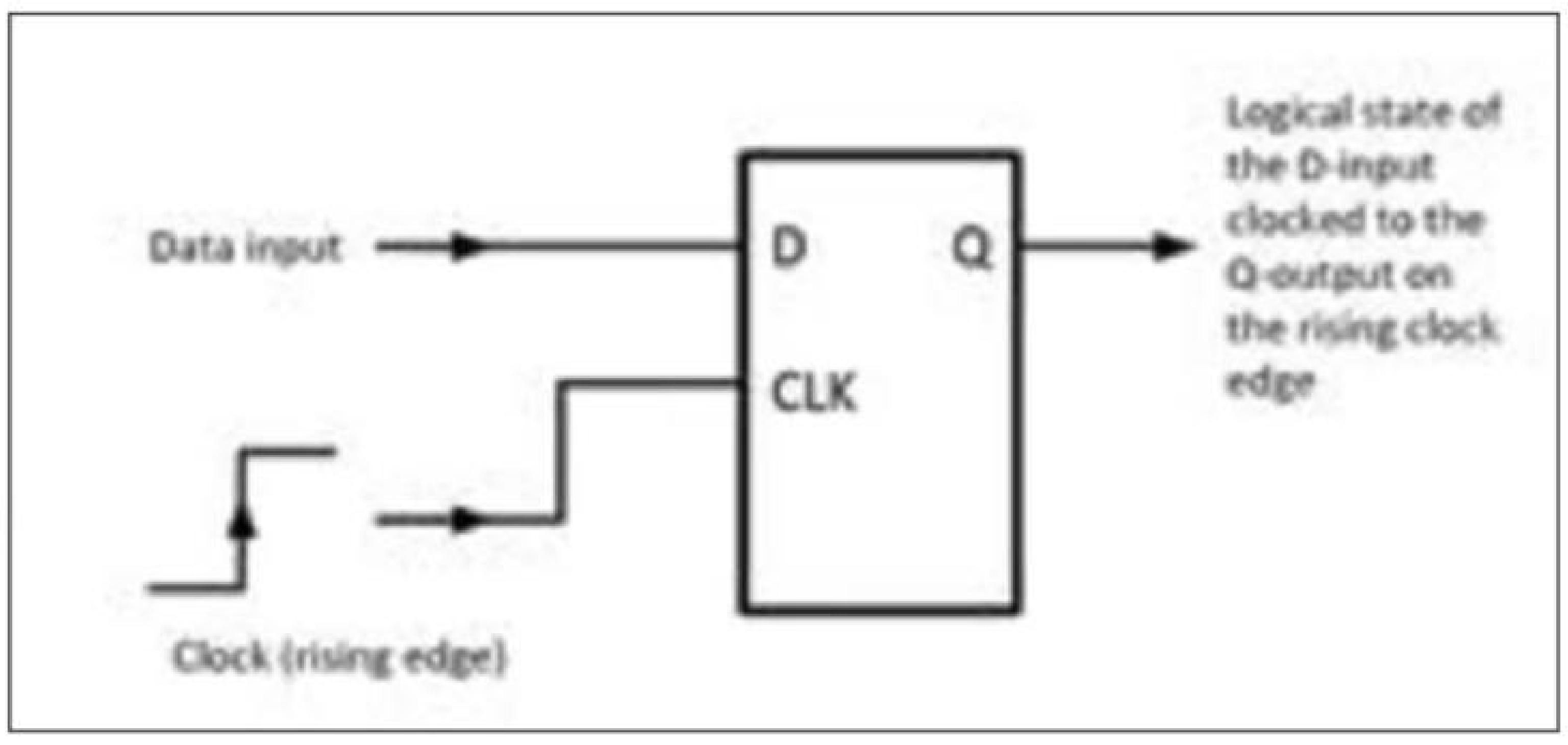

Data input
D
Q
CLK
Clock (rising edge)
Logical state of the D-input clocked to the Q-output on the rising clock edge

Fig.14.5. (right) Clocking a D-type bistable element to change its output state.

NOR
Likewise, a NOR gate ('not-OR') will only produce a logic 1 output when all inputs are simultaneously at logic 0. Any other input combination will produce a logic 0 output. A NOR gate, therefore, is simply an OR gate with its output inverted, or an OR gate followed by an inverter. Again, a circle is used to indicate inversion.

XOR
The exclusive-OR (XOR) gate produces a logic 1 output whenever either one of inputs is at logic 1 providing the other input is at logic 0 – they only ever have two inputs. Exclusive-OR gates produce a logic 0 output whenever both inputs have the same logical state (ie, when both are at logic 0 or both are at logic 1).

Monostable and bistable elements

A logic device which has only one stable output state is known as a monostable. The output of such a device is initially at logic 0 (low) until an appropriate level change occurs at its trigger input. This level change can be from 0 to 1 (called 'positive-edge trigger') or 1 to 0 (called 'negative-edge trigger') depending upon the particular device or configuration. Upon receipt of a valid trigger pulse the output of the monostable changes state to logic 1. Then, after a time interval determined by external *RC*-timing components (a resistor and capacitor), the output reverts to logic 0. The device then stays at logical 0 output until the arrival of the next trigger. A typical application for a monostable device is in stretching a short duration pulse.

By contrast, the output of a bistable has two stable states (logic 0 or logic 1) and, once set the output of the device will remain at a particular logic level for an indefinite period until reset. A bistable thus constitutes a simple form of memory because it will remain in its latched state (whether 'set' or 'reset') until commanded to change its state (or until the supply is disconnected). Various forms of bistable are available including R-S, D-type and J-K-types (see Fig.14.3).

R-S bistables
The R-S bistable is the most basic form of bistable. The device has two inputs, SET and RESET, and complementary outputs, Q and $\overline{Q}$ (the inverse of Q). A logic 1 applied to the SET input will cause the Q output to become (or remain at) logic 1, while a logic 1 applied to the RESET input will cause the Q output to become (or remain at) logic 0. In either case, the bistable will remain in its SET or RESET state until an input is applied in such a sense as to change it. R-S bistables can be easily implemented using cross-coupled NAND or NOR gates, as shown in Fig.14.4. These arrangements are, however, unreliable as the output state is indeterminate when both the SET and RESET inputs are simultaneously at logic 1.

D-type bistables
The D-type bistable has two principal inputs: D (standing variously for 'data' or 'delay') and CLOCK (written as CK or CLK). The data input (logic 0 or logic 1) is clocked into the bistable such that the output state only changes when the clock changes state (see Fig.14.5). Operation is thus said to be synchronous. Additional subsidiary inputs (which are invariably active low) are provided which can be used to directly set or reset the bistable. These are usually called PRESET (PR) and CLEAR (CLR). D-type bistable elements can be used both as 'latches' (a simple form of memory) and as binary dividers.

J-K bistables
J-K bistables are the most sophisticated and flexible of the bistable types and they can be configured in various ways, including binary dividers, shift registers, and latches. J-K bistables have two clocked inputs (J and K), two direct inputs (PRESET and CLEAR), a CLOCK (CK) input, and outputs (Q and $\overline{Q}$). As with R-S bistables, the two outputs are complementary (ie, when one is 0 the other is 1, and vice versa). Similarly, the PRESET and CLEAR inputs are invariably both active low (ie, a 0 on the PRESET input will set the Q output to 1 whereas a 0 on the CLEAR input will set the Q output to 0).

Logic families

Digital integrated circuit devices are often classified according to the semiconductor technology used in their fabrication. The logic 'family' to which a device belongs being largely instrumental in determining its operational characteristics (such as power consumption, speed, and immunity

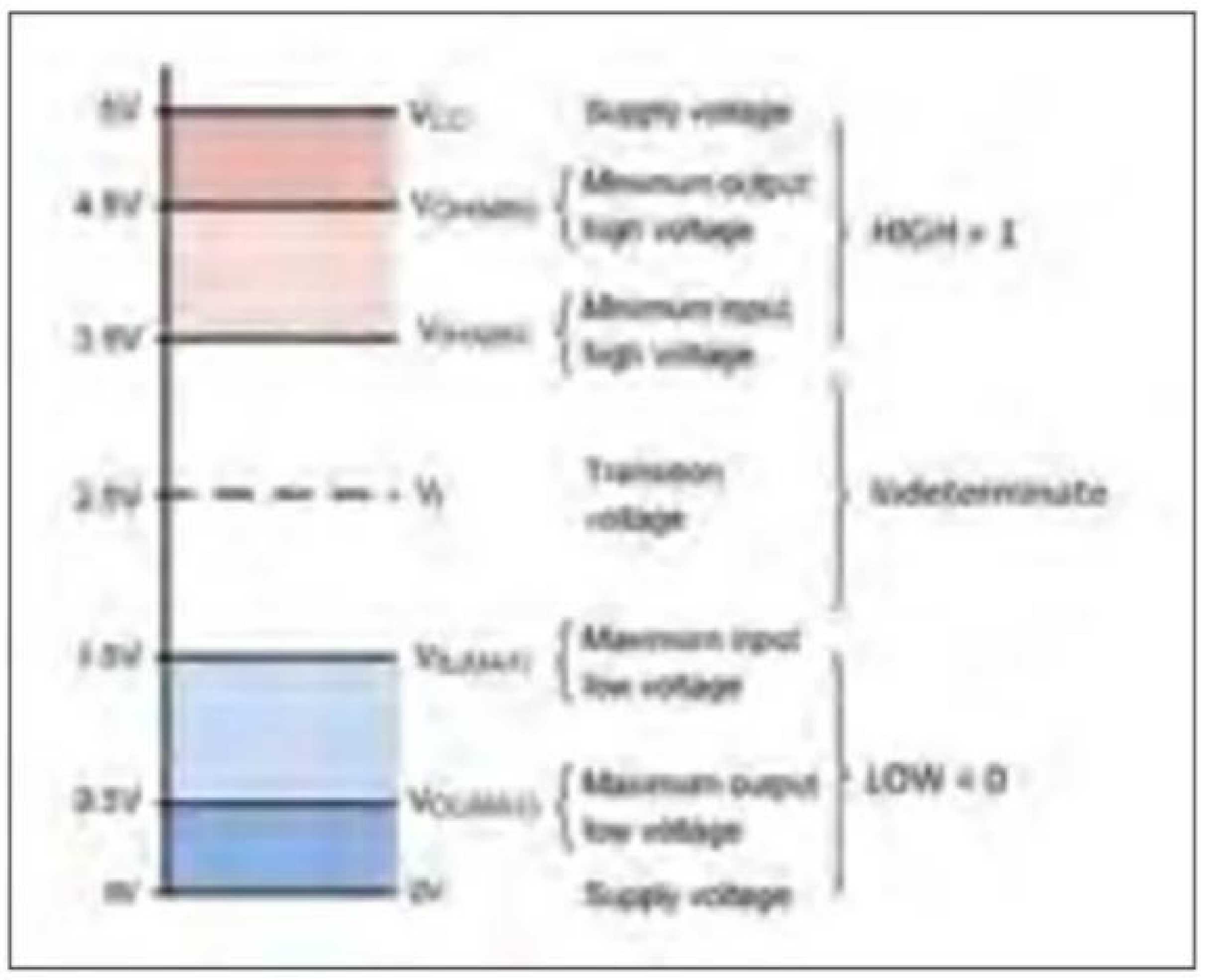

5V
V_{CC}
Supply voltage
Minimum output high voltage
Minimum input high voltage
HIGH = 1
V_t
Transition voltage
Indeterminate
Maximum input low voltage
Maximum output low voltage
LOW = 0
0V
Supply voltage

Fig.14.6. Standard logic levels for HC-series logic devices.

Table 14.1 HC-logic family characteristics

Symbol	Parameter	Value			Units
		Min	Typ	Max	
V_{CC}	Supply voltage	2.0	5.0	6.0	V
V_I	Input voltage range (note 1)	0	n/a	V_{CC}	V
V_O	Output voltage range (note 1)	0	n/a	V_{CC}	V
t_r, t_f	Rise/fall time (note 2)	0	6.0	500	ns
V_{IH}	Input high voltage (note 2)	3.5	4.8	5.0	V
V_{IL}	Input low voltage (note 2)	0	0.2	1.5	V
V_{OH}	Output high voltage (note 2)	4.5	4.9	5.0	V
V_{OL}	Output low voltage (note 2)	0	0.1	0.5	V

Notes
1. Must not be outside the quoted range
2. Values are quoted for a typical VCC of 5V

Table 14.2 Common HC-logic family devices

Device	Logic function	Package (DIL versions)
74HC00	Quad 2-input NAND	14-pin
74HC02	Quad 2-input NOR	14-pin
74HC04	Hex inverter	14-pin
74HC08	Quad 2-input AND	14-pin
74HC14	Hex Schmitt inverter	14-pin
74HC32	Quad 2-input OR	14-pin
74HC73	Dual J-K bistable (with preset and clear)	14-pin
74HC74	Dual D-type bistable (positive edge trigger)	14-pin
74HC123	Dual monostable (can be retriggered)	16-pin
74HC138	3-to-8-line decoder	16-pin
74HC164	8-bit serial input shift register	14-pin
74HC165	8-bit parallel input shift register	16-pin
74HC595	8-bit serial to parallel shift register	16-pin

to noise). The two most important legacy logic families are CMOS (Complementary Metal-Oxide Semiconductor) and TTL (Transistor-Transistor Logic). Over the past 50 years each of these families has been extended and further sub-divided. The most appropriate logic family for use in our *Quiz Machine* uses high-speed CMOS technology. This 'HC-family' of devices combines several of the desirable characteristics of CMOS technology with traditionally faster and more robust TTL logic.

Logic levels

Logic levels are simply the range of voltages used to represent the logic states 0 and 1. The logic levels for HC-family devices are similar to those used by standard CMOS logic and differ from those associated with conventional TTL and LS-TTL devices. Fig.14.6 illustrates the usual range of voltage and corresponding logic levels used with HC-family devices. There are a few important things to consider from Fig.14.6:

1. The minimum output high voltage (V_{OHmin}) must be greater than the minimum input high voltage, V_{IHmin}.
2. The maximum output low voltage (V_{OLmax}) must be less than the maximum input low voltage, V_{ILmax}.
3. The circuit designer must take steps to ensure that the input high (V_{IH}) and input low (V_{IL}) voltages are well within the acceptable range. Failure to do this may well result in unpredictable performance.
4. The transition voltage (V_t) is nominally at 50% of the supply voltage, V_{CC}. When the input logic levels change rapidly from 0 to 1 or 1 to 0 it is usually assumed that the change of output state occurs at this point.

It is important to note that HC-devices are capable of operating at conventional TTL supply voltages (5V ± 10%) and also with the usual range of input levels used by standard TTL devices. They can thus be used as pin compatible TTL replacements to reduce power consumption without loss of speed. Some typical HC-family specifications are summarised in Table 14.1 and some common devices are listed in Table 14.2, together with their logic function.

Unlike earlier CMOS and MOS devices, the inputs and outputs of HC-series devices are protected against electrostatic discharge that may occur in typical handling situations. That said, it is always wise to get into the habit of observing ESD precautions when handling or using these devices (see *Going further*).

In some applications you might find that you don't need to use all the logic elements provided within a particular IC package (eg, you might only need two of the four NOR gates within a 74HC02 package). If that's the case, it's important to follow manufacturers' recommendation concerning unused inputs and outputs. Generally, this means that unused inputs should be tied to V_{CC} while unused outputs are simply left floating. In addition, a capacitor of typically 100nF should be connected as close as possible between the V_{CC} and GND pins of each logic device (ie, between pin-7 and pin-14 of a 74HC02). Failure to observe these precautions can sometimes result in unreliable operation, oscillation and instability.

Design specification

As with any electronic design project, it is important to start with a sufficiently detailed specification. Our *Quiz Machine* is to have two momentary action pushbuttons, one for each team. When either of the buttons is operated, an LED should light to identify the answering team. So that there's no uncertainty as to which of the teams has answered first, the button for the other team must be 'locked out'. Once the answer has been evaluated the quiz master can clear the state of the LEDs

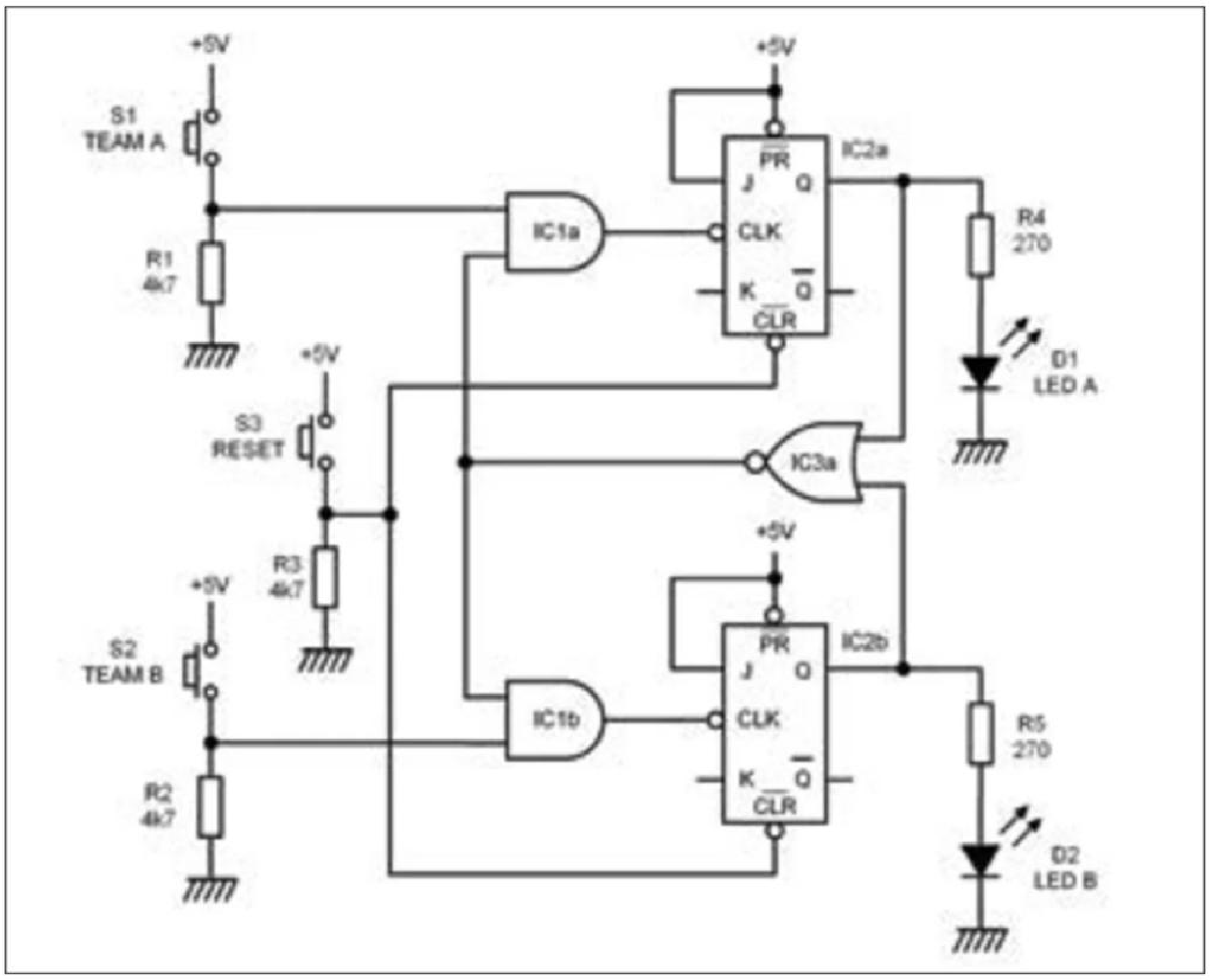


Fig.14.7. *Quiz Machine* based on logic gates and J-K bistable elements.

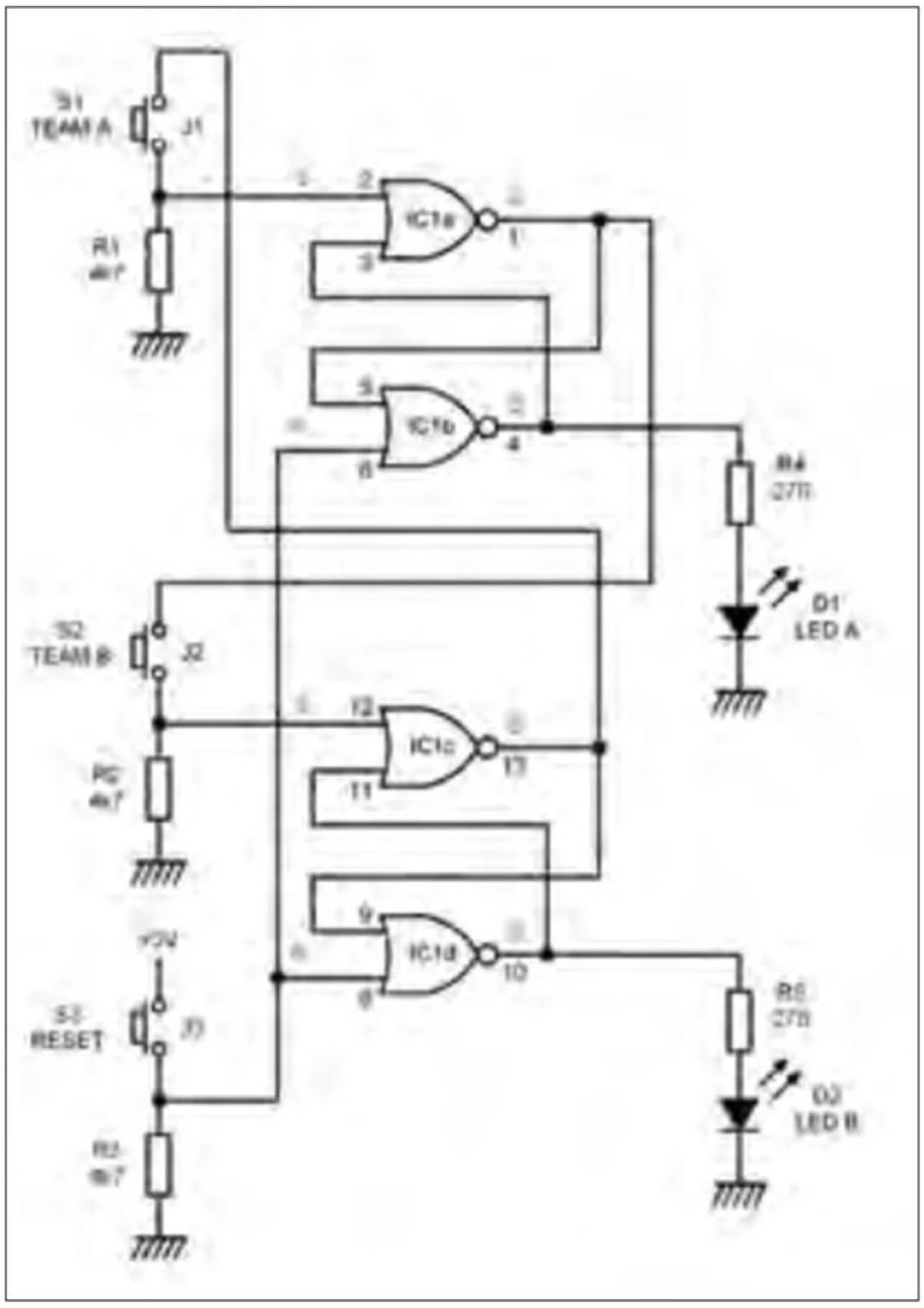


Fig.14.8. Minimised version of the *Quiz Machine* logic using two pairs of cross-coupled, two-input NOR gates.

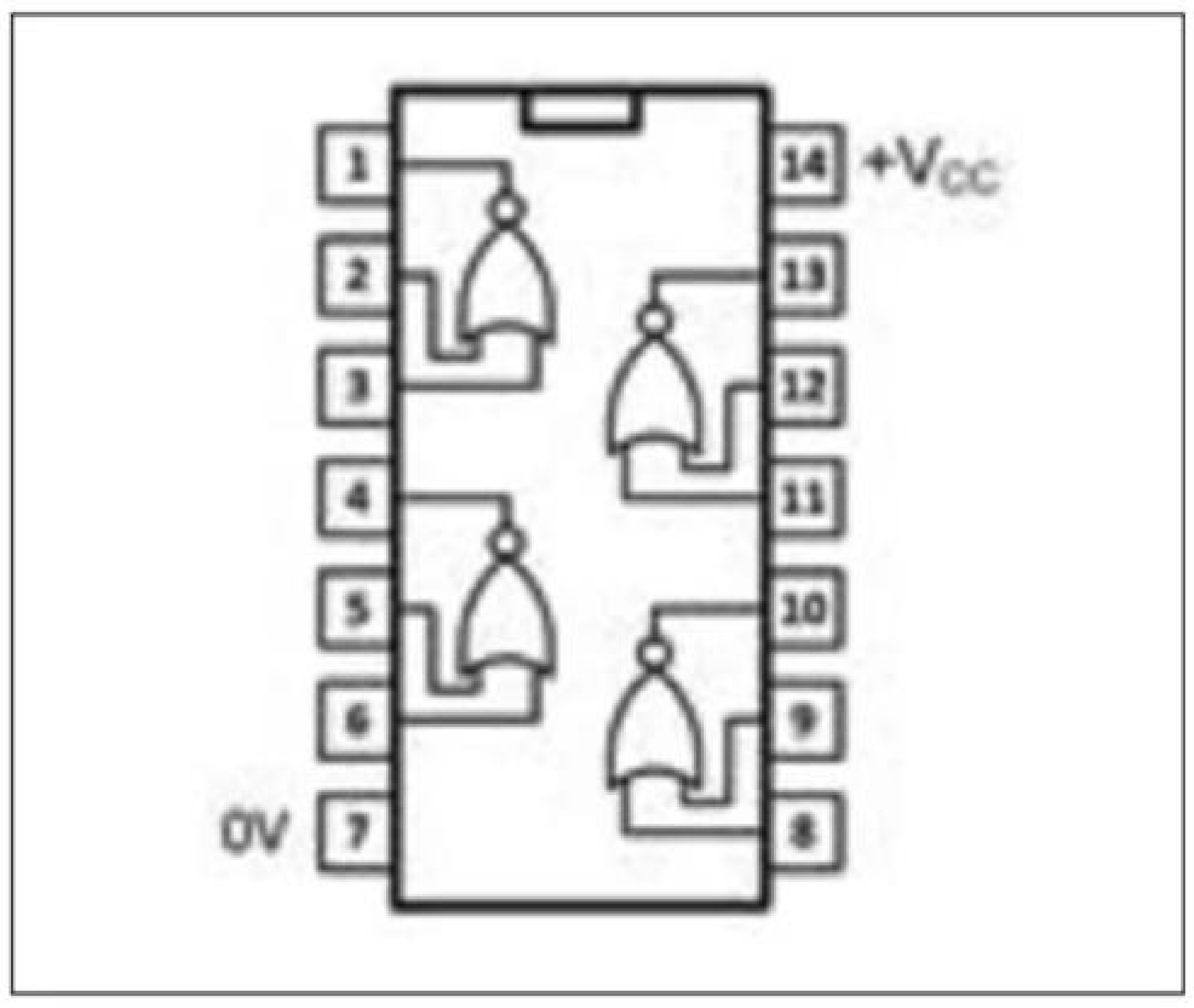


Fig.14.9. Pin connections for the 74HC02 quad two-input NOR gate.

using the RESET button before awaiting an answer to the ensuing question.

We thus have three momentary-action pushbutton inputs which will be labelled ‘TEAM A’, ‘TEAM B’ and ‘RESET’. The outputs will be two large LED indicators which can later be augmented by external lamps and buzzers (if or when the need arises). The circuit is to operate from a low-voltage 5V supply and be small enough to fit into a small ABS enclosure.

Memory

From the design specification is should be obvious that the *Quiz Machine* needs to ‘remember’ that one or other of the TEAM buttons has been pressed. Once pressed, it should not be necessary to hold the pushbutton down continuously. In a microcontroller application this can be achieved by reading the state of the two TEAM buttons and then setting or resetting variables accordingly. With the ‘legacy logic’ version this ‘memory feature’ can be realised by using the button status to set a bistable element. Note that we will need two bistable elements, one for each of the TEAM button inputs. We also need to ensure that once one of the two bistable elements has been SET the other bistable should no longer be able to react to a button press (thus ‘locking out’ the other team’s pushbutton). This can be achieved by using some simple logic, as shown in Fig.14.7. This arrangement can be realised using a total of three dual-in-line chips, a 74HC02, 74HC08 and 74HC73 (see Table 14.2).

When working with logic circuits it is often possible to minimise a design and the arrangement shown in Fig.14.7 should just be considered a good starting point. If we replace the two J-K bistable elements with cross-coupled NOR gates we can reduce the device count by one. A further reduction can be made by using the two $\overline{Q}$ outputs to provide the logic HIGH state for the push-button inputs (instead of simply connecting the pushbuttons to the +5V supply). This minimised arrangement is shown in Fig.14.8 and it uses a single 74HC02 logic device (see also Fig.14.9).

Simulation

Before arriving at a breadboard layout, it is well worth checking the prototype design using a simulation package such as Tina or Deeds. This will allow you to assemble a ‘virtual circuit’ and check that it all works as intended. Figs.14.10 and 14.11 show how this can be done. Each of the inputs (SW1, SW2 and SW3) can be operated while observing the state of the two outputs (D1 and D2). It is also important to check that the RESET button (SW3) operates correctly and that the ‘lockout’ feature works as planned.

Breadboarding

Having checked the circuit simulation (and before moving on to the final prototype stage) it can be useful to assemble the circuit on a breadboard using physical component parts, as shown in Fig.14.12. This may occasionally reveal differences between the behaviour of virtual component models and their physical counterparts. It will also provide you with a further opportunity to confirm your design before committing it to a stripboard or a (somewhat more expensive) printed circuit board layout. Note that coloured

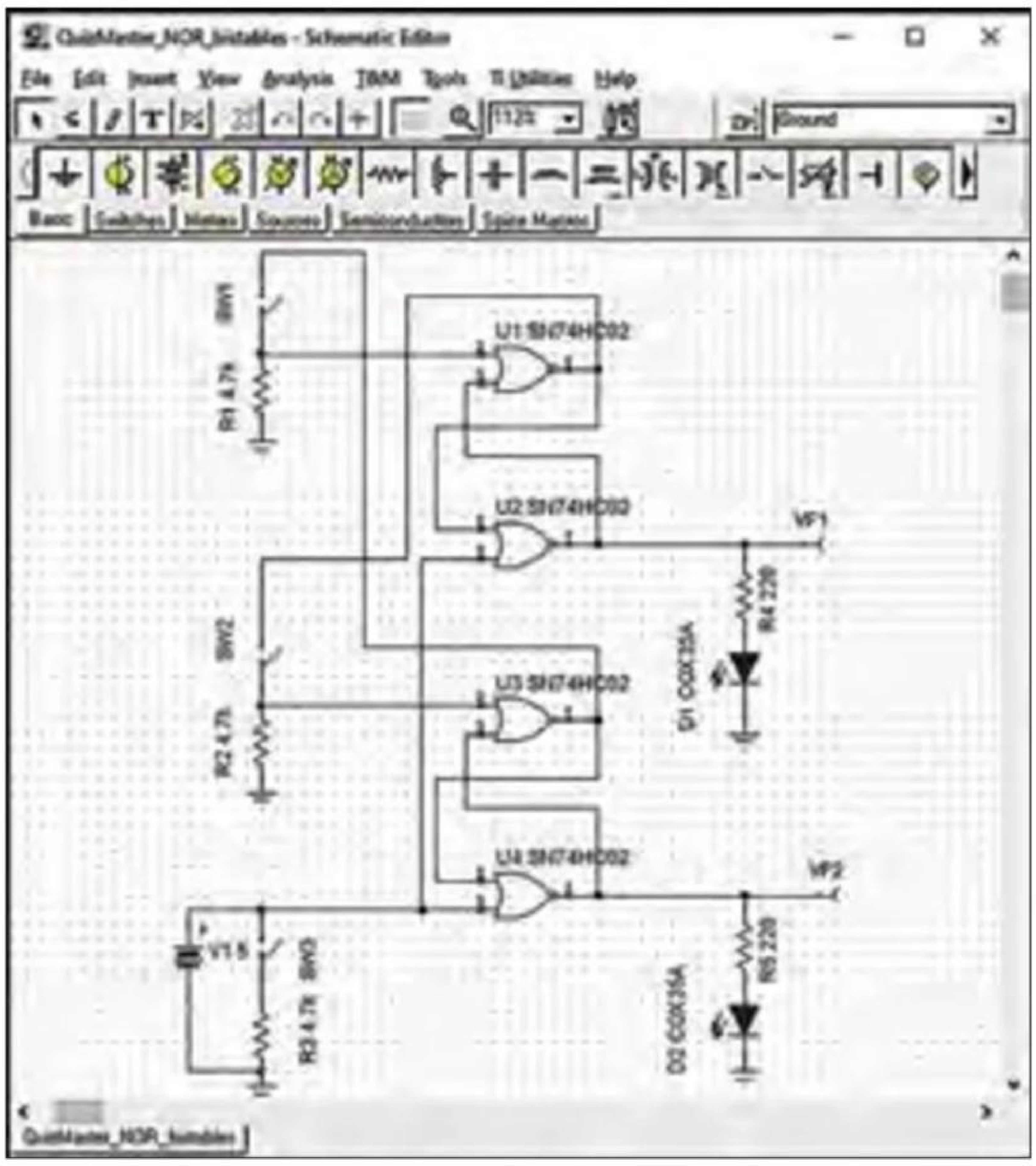

QuizMaster_NOR_bistables - Schematic Editor
File Edit Insert View Analysis T&M Tools TI Utilities Help
112%
Ground
Basic Switches Meters Sources Semiconductors Spice Macros
SW1
R1 4.7k
U1 SN74HC02
U2 SN74HC02
VF1
R4 220
D1 COX35A
SW2
R2 4.7k
U3 SN74HC02
U4 SN74HC02
VF2
V1 5
SW3
R3 4.7k
R5 220
D2 COX35A
QuizMaster_NOR_bistables

Fig.14.10. Simulating the circuit in Fig.14.8 using Tina Pro.

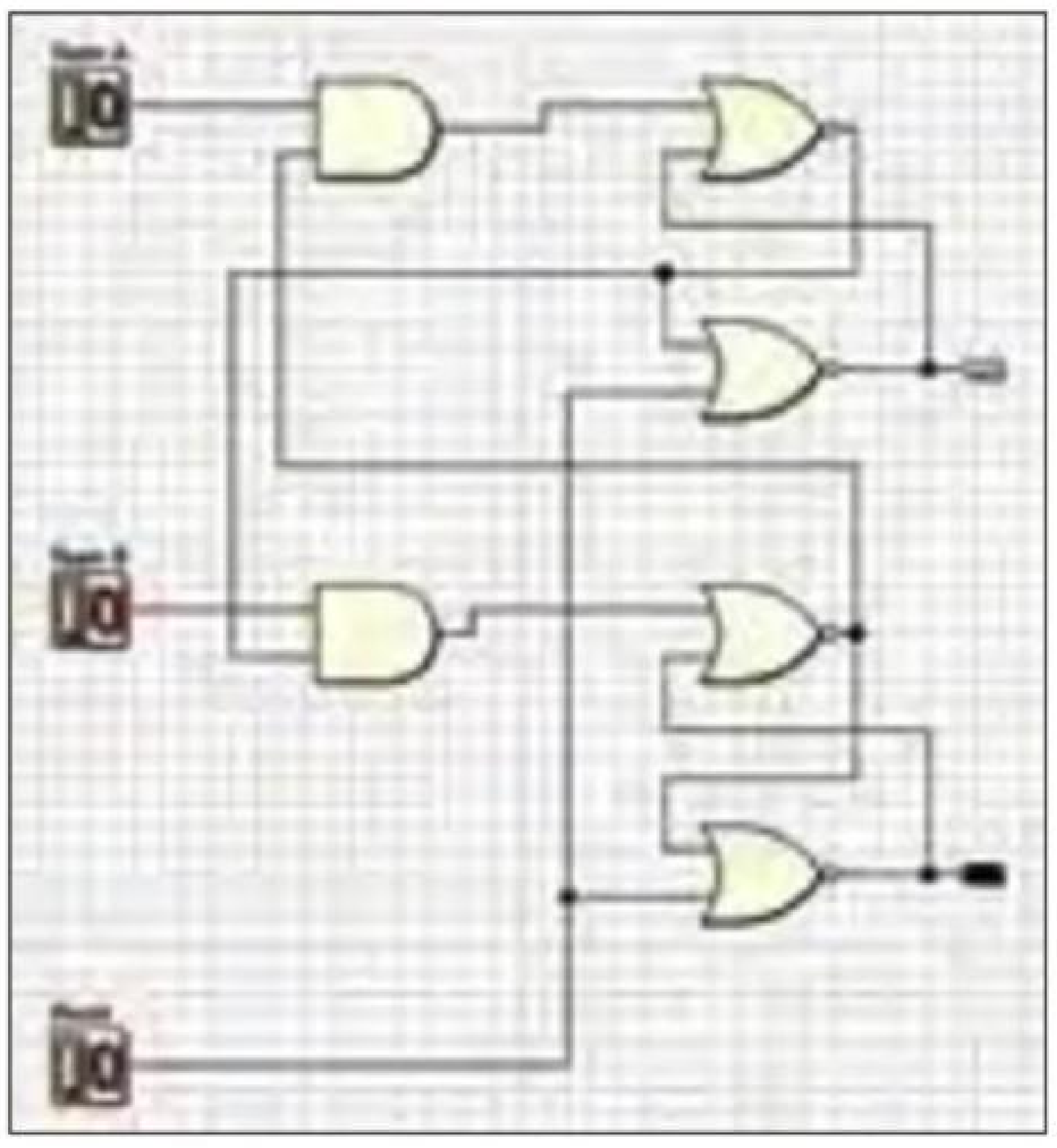


Fig.14.11. (right) Simulating an earlier version of the circuit using the Deeds digital logic environment.

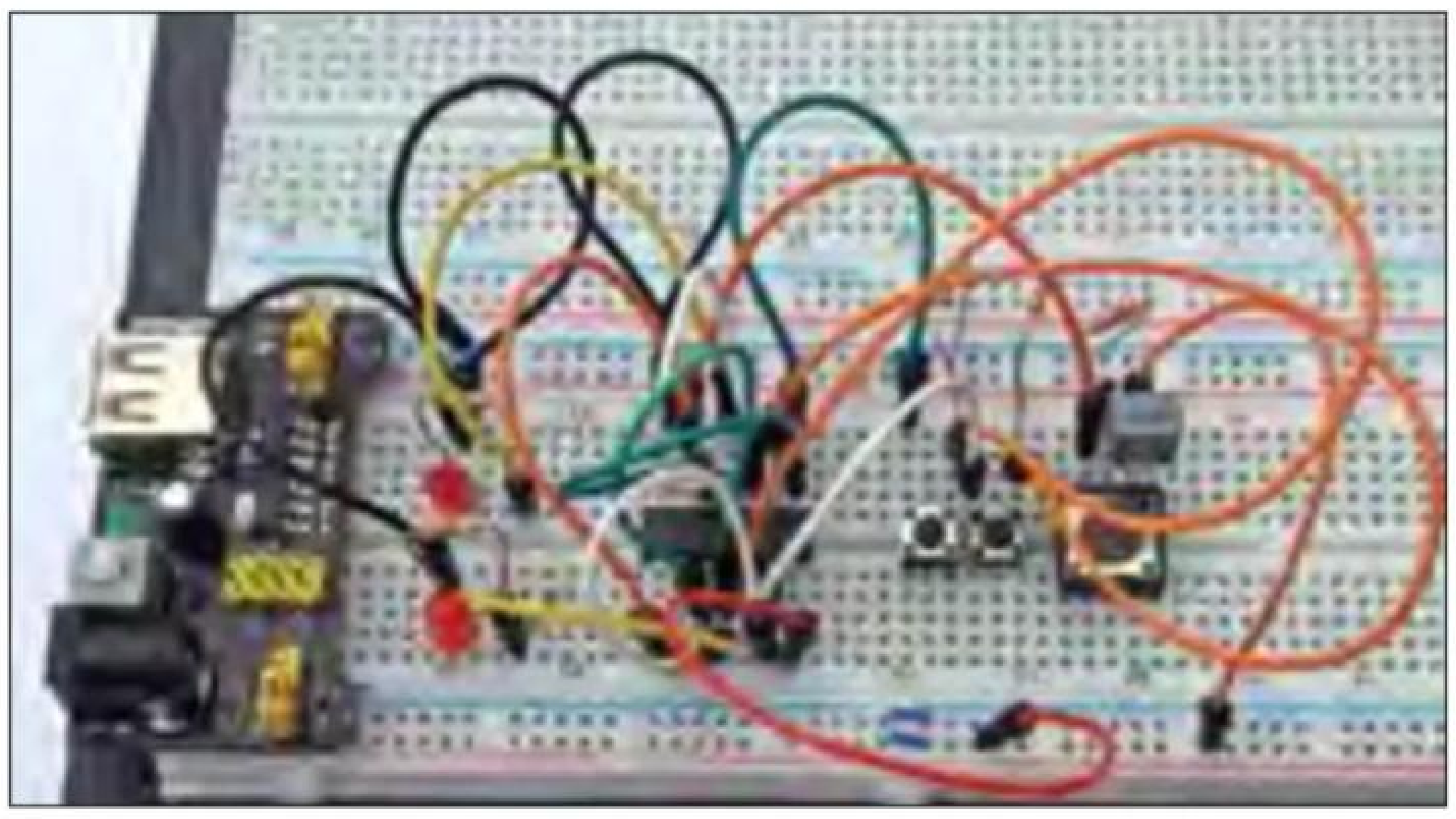
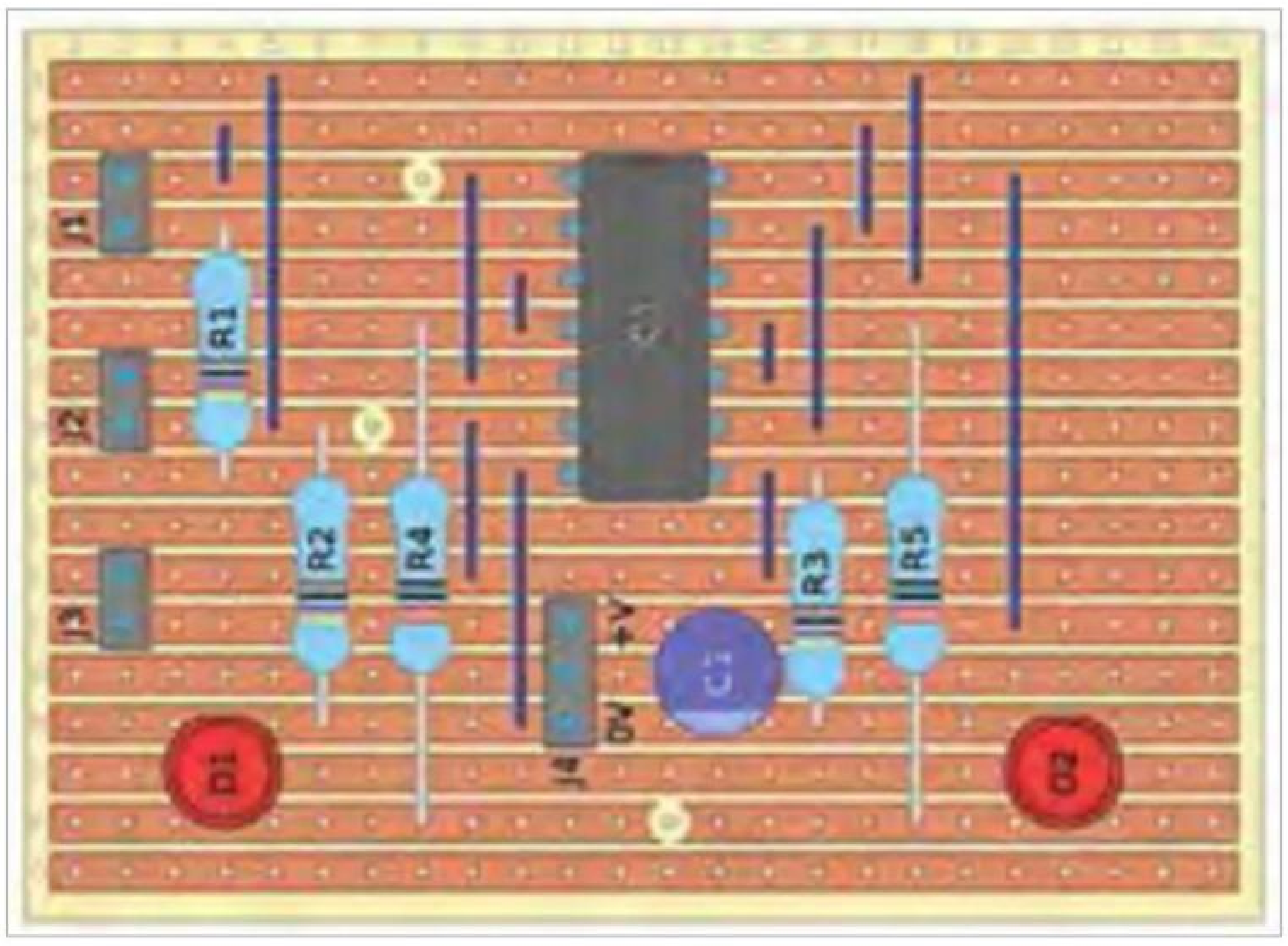


Fig.14.12. Breadboard testing the circuit in Fig.14.8.

Table 14.3 Going further with legacy logic

Topic	Source	Notes
Logic families	Texas Instruments (TI) provides an excellent overview of the different families of logic.	The *Texas Instruments Logic Guide* is available from: **https://bit.ly/pe-dec23-ti**
HC-series logic	The Toshiba HC-series application note provides useful information and detailed technical specifications. HC-series logic chips can be obtained from most electronic component suppliers.	The Toshiba application note is available from: **https://bit.ly/pe-dec23-tosh**
Deeds simulation software	Conceived as a common resource for working in digital electronics, the Deeds environment is an excellent learning resource that allows you to quickly and easily build, test and refine your digital logic circuits	The Deeds simulation package can be freely downloaded from: **https://bit.ly/pe-dec23-deeds**
Tina simulation software	The powerful and intuitive Tina Design Suite from DesignSoft can help you simulate a vast range of analogue and digital circuits.	**A** special Texas Instruments version of the software, Tina-TI, can be downloaded for free from: **https://bit.ly/pe-dec23-tinati** The Student and Full/Hobbyist versions of Tina Design Suite can be purchased from the PE website. Budget versions of the software available are available for students and hobbyists respectively at: **https://bit.ly/pe-dec23-tinastud** **https://bit.ly/pe-dec23-tinahob**
Logic circuits	For those with no previous experience, *Part 4* of *Electronics Teach-in 4* (from Electron Publishing) provides a basic introduction to logic circuits. It also shows how the popular Circuit Wizard software can be used to simulate and test practical logic designs	Available (as part of a Teach-in bundle) from Electron Publishing at: **https://bit.ly/pe-dec23-eti345**
Logic circuits and simulation techniques	The author's own book, *Electronic Circuits: Fundamentals and Applications* (Fifth Edition 2020 published by Routledge 9780367421984) includes a general introduction to logic circuits and simulation techniques.	Available from Electron Publishing at: **https://bit.ly/pe-dec23-mtoo**

Fig.14.13. Stripboard prototype layout for the circuit in Fig.14.8. (Not shown, but important: track cuts C-I 12 between IC pins.)


J1
J2
J3
R1
R2
R4
R3
R5
J4
+V
0V
C1
D1
D2

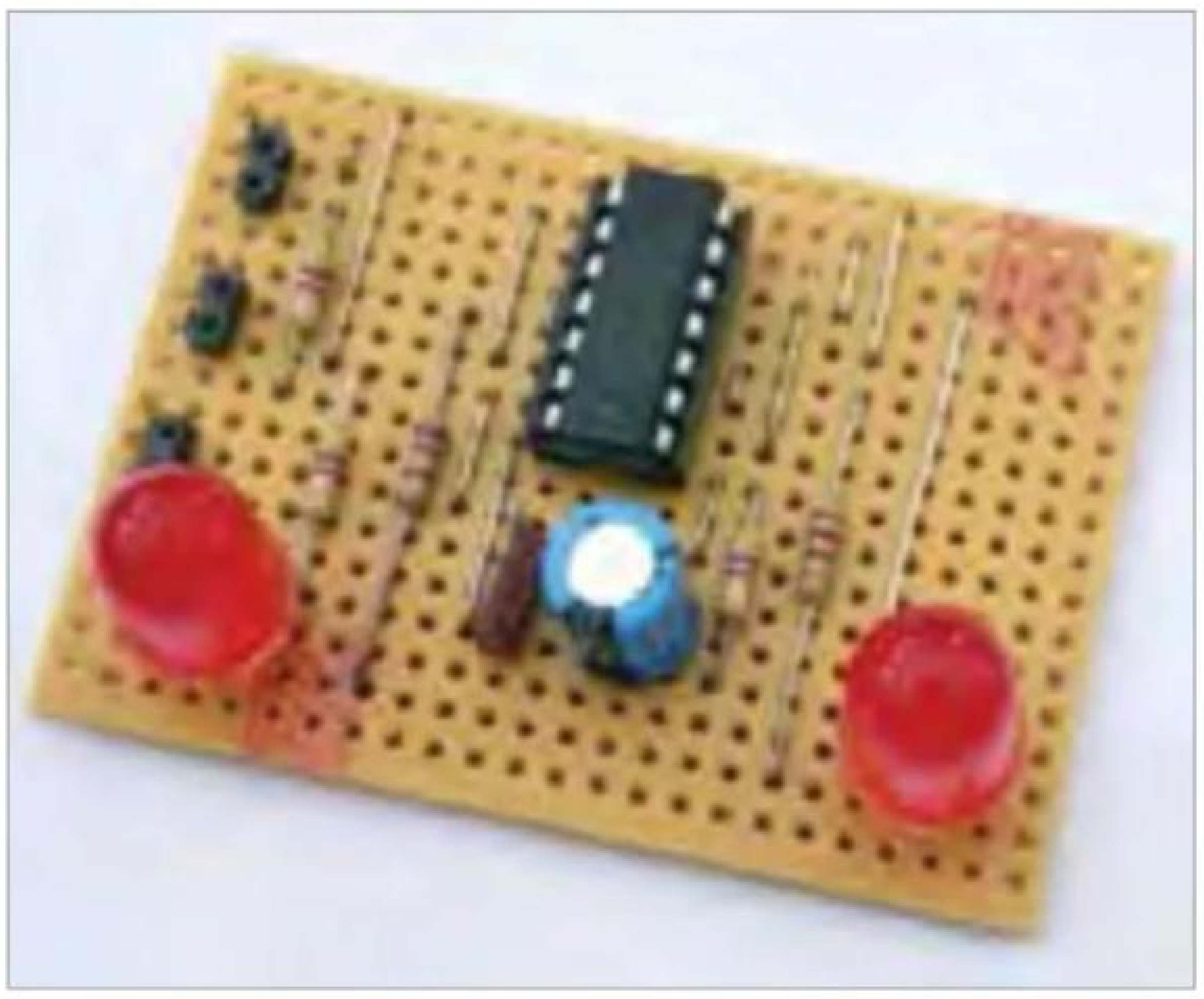


Fig.14.14. The completed prototype ready for testing.

interconnecting wires will help reduce some of the potential confusion when it comes to the wiring arrangement of a large breadboard circuit.

Prototype

The prototype layout for the *Quiz Machine* is shown in Fig.14.13. This uses a small piece of stripboard (17 strips by 24 holes). Note that all the tracks beneath IC1 must be broken (not shown in Fig.14.13). The completed prototype (ready for testing) is shown in Fig.14.14.

Finally, to provide you with some extra 'food for thought', Fig.14.15 provides some circuit fragments from the author's recent use of 'legacy logic'. So, if you have a simple application it could be that 'legacy logic' will provide you with an easy and inexpensive solution without having to resort to a complex and expensive microcontroller design!

Going further

This section details a variety of sources that will help you locate the component parts and further information that will allow you to make and use legacy logic in your own applications. It also provides some useful links that will help you get up to speed with the necessary underpinning knowledge for the key topics discussed.

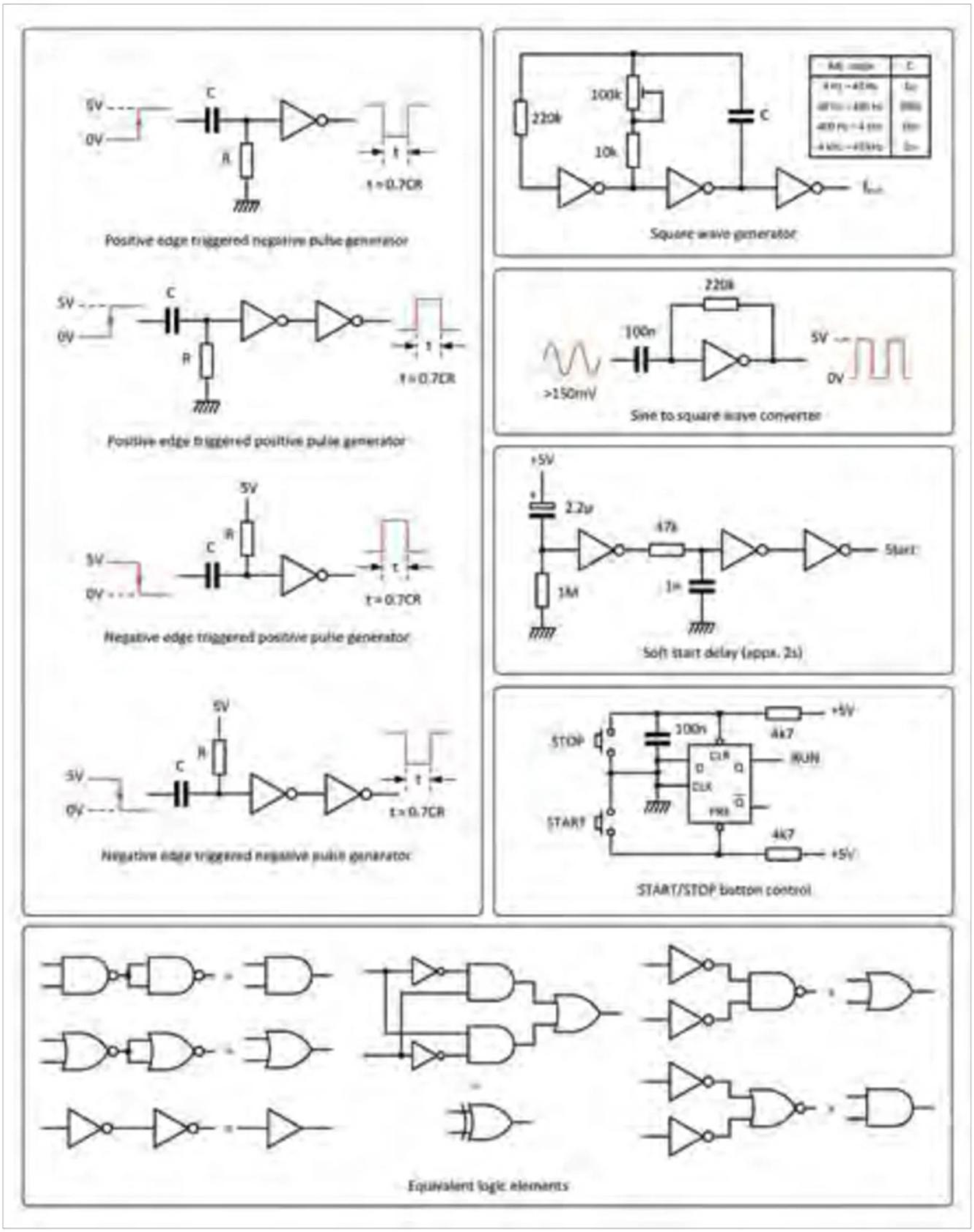

5V
0V
C
R
t
t = 0.7CR
Positive edge triggered negative pulse generator
5V
0V
C
R
t
t = 0.7CR
Positive edge triggered positive pulse generator
5V
R
C
5V
0V
t
t = 0.7CR
Negative edge triggered positive pulse generator
5V
R
C
5V
0V
t
t = 0.7CR
Negative edge triggered negative pulse generator
220k
100k
10k
C
Square wave generator
220k
100n
>150mV
5V
0V
Sine to square wave converter
+5V
2.2µ
47k
1M
1n
Start
Soft start delay (appx. 2s)
STOP
START
100n
4k7
+5V
RUN
CLR
D
Q
CLK
PRE
4k7
+5V
START/STOP button control
Equivalent logic elements

Fig.14.15. Some useful circuit arrangements based on 'legacy logic'.

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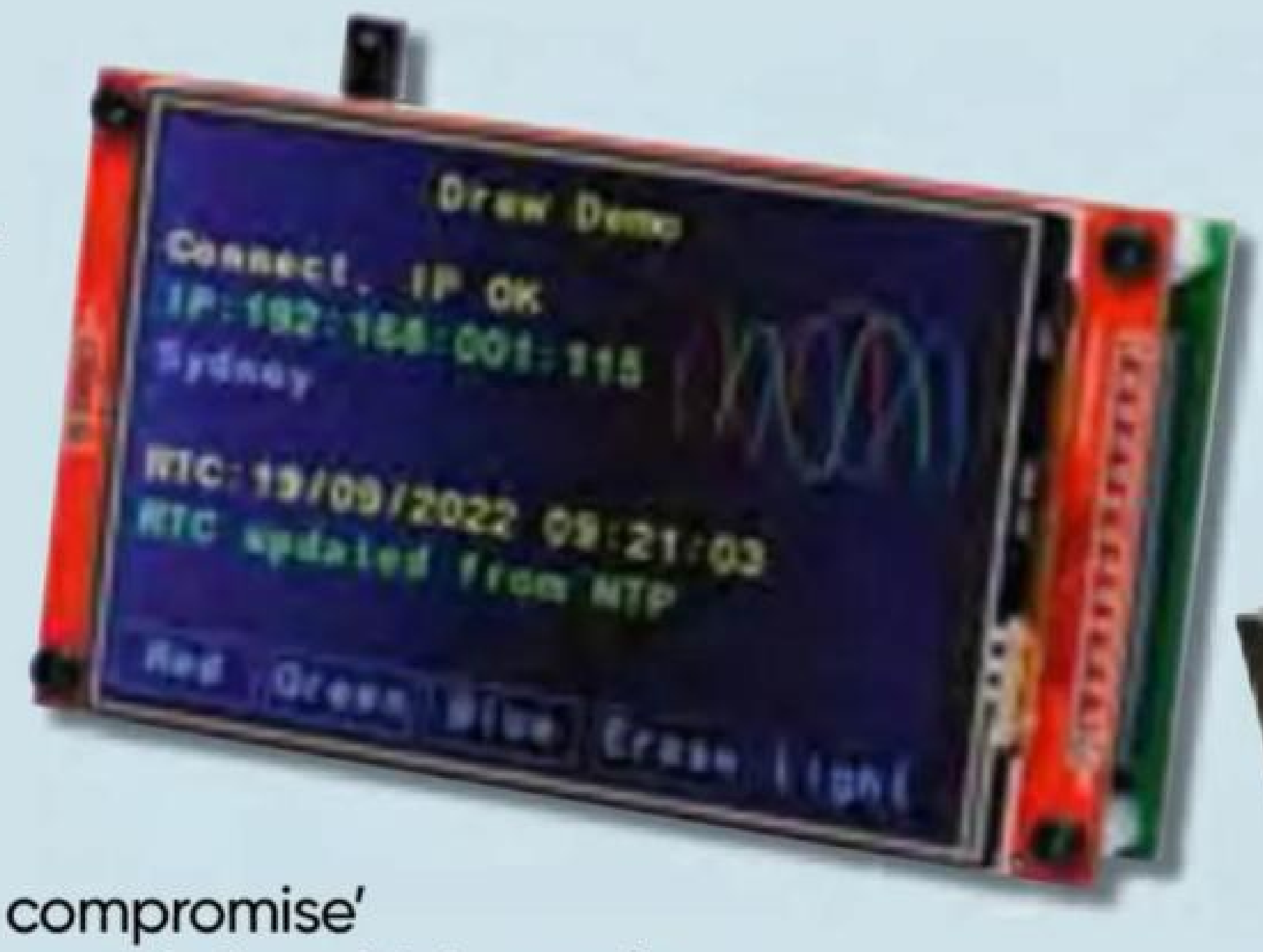
For editorial contact details see page 7.

Next Month – in the January issue

Q Meter

We've published numerous LC meters that can measure inductance and capacitance, but you might need to know the quality factor (Q) of an inductor, not just its inductance. This Q Meter uses a straightforward circuit to measure the Q factor over a wide range, up to values of about 200.



Raspberry Pi Pico BackPack

Our Raspberry Pi Pico BackPack from March 2023 has a powerful dual-core 32-bit processor, 480 × 320 pixel colour touchscreen, onboard real-time clock, SD card socket, stereo audio output and infrared receiver. Now, for only a little more expense, it has WiFi too!

Active Subwoofer

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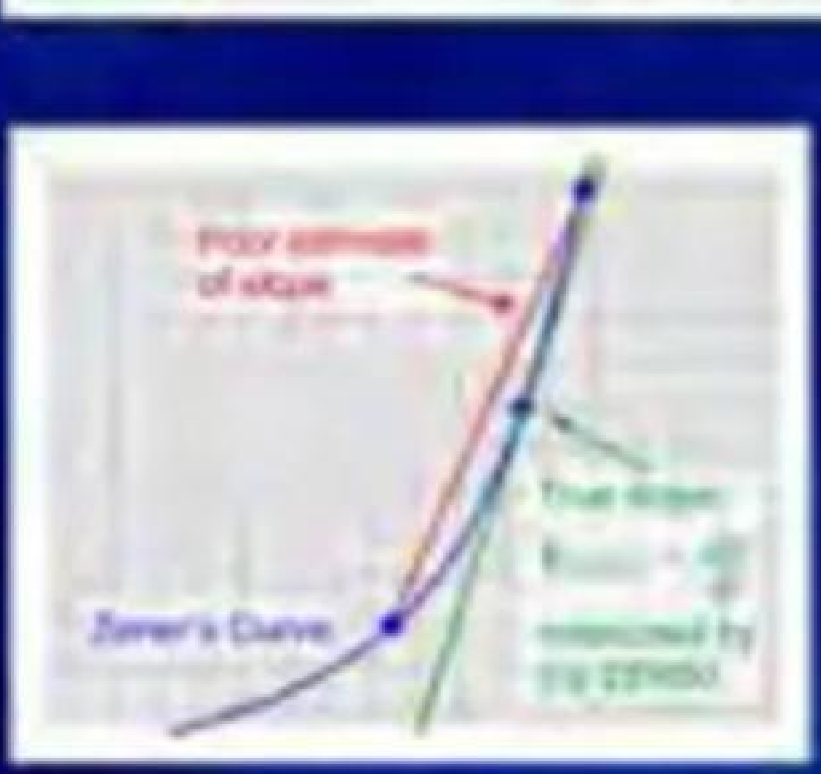

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